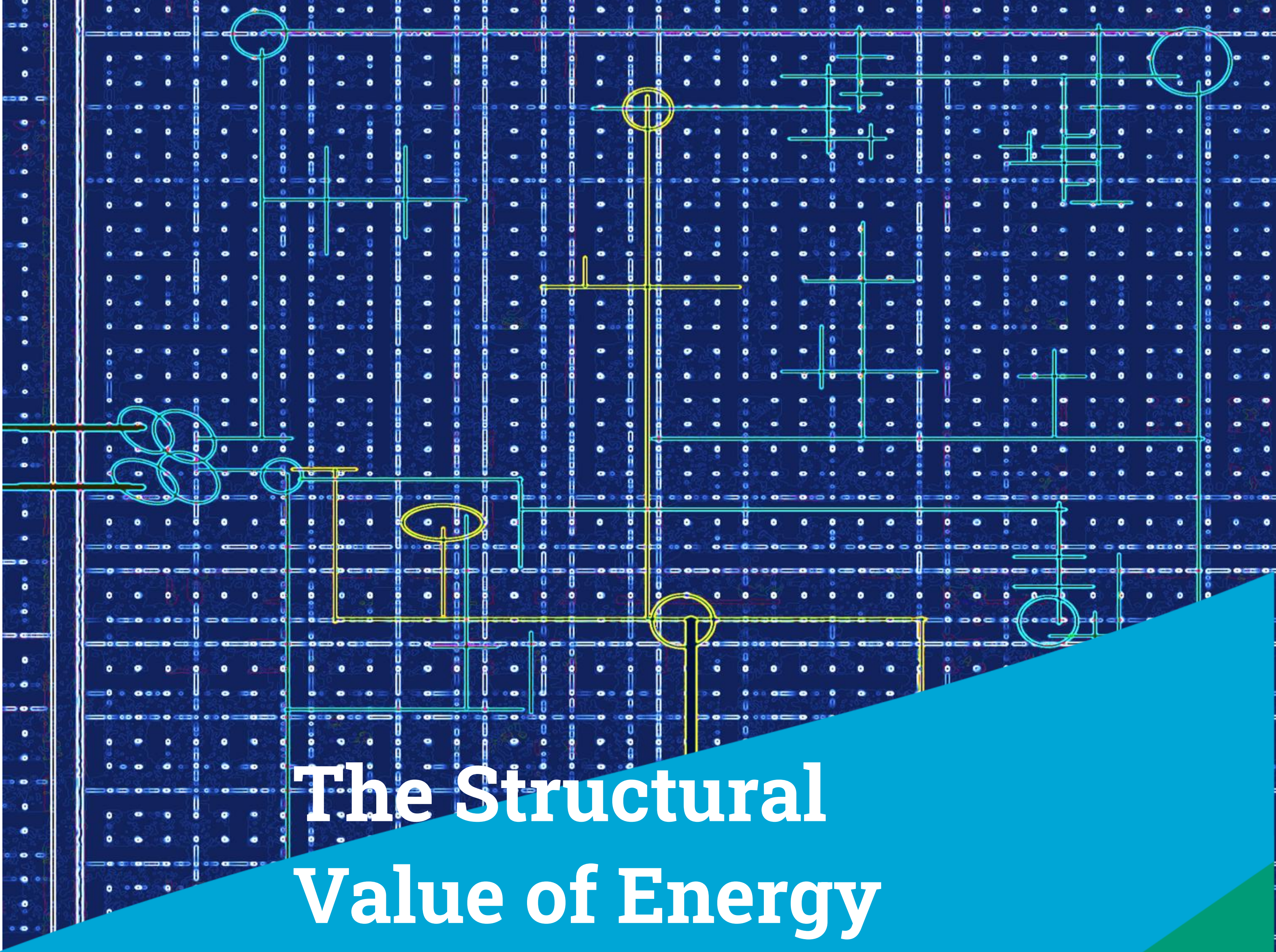

The Structural Value of Energy Hubs

The communal value of multi-carrier energy-hubs in the energy system of the future.

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TU Delft

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The Communal Value of Multi-carrier Energy-hubs in the Energy System of the Future.

By

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Preface

What lies before you is both a significant challenge and a passionate project, my master's thesis, which has defined the past months of my academic and personal life.

This journey has taught me a tremendous amount: not only about the technical and societal dimensions of energy system integration, but also about the process of research, resilience, and the importance of support.

I would first like to express my sincere gratitude to my direct supervisors at Stedin, Arjen and Tim, and Laurens and Aad at the TU. Their steady guidance and encouragement played a crucial role in the development of this work. I especially want to thank the company Stedin, which not only provided direction but also gave me the freedom to put my own spin on the research. I am equally thankful to my academic supervisors, both of whom are experts in the field and deeply knowledgeable about the topic that drives my curiosity: the integration of energy systems. Their combined knowledge and experience have been a source of inspiration, and it was a privilege to benefit from their collective counsel throughout this process.

While I expected this thesis to be demanding, I didn’t fully anticipate the kinds of challenges I would encounter. At moments when I lost oversight or got stuck in complexity, it was thanks to the experience and support of my supervisors that I was able to regain focus and move forward. I also faced unexpected health issues during this time, which at points made it difficult or even impossible to continue working. I initially hesitated to acknowledge these struggles, driven by a strong desire to stay on track and meet deadlines. Yet, through these experiences, and the patient support of my supervisors, I learned that not everything can be forced. Some processes simply take time.

Beyond the academic sphere, I am deeply grateful to my friends, family, and partner. While I was immersed in writing and research, they were there to help me gain perspective, offer guidance, and support me through personal setbacks. Their encouragement and presence made a lasting difference. To everyone who has walked part of this journey with me—thank you.

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Executive Summary

Introduction and RQ

The Dutch energy system is undergoing significant change, marked by increased electrification, decentralization of energy sources, and a growing reliance on renewable energy.
These developments lead to a scarcity in transmission capacity known as grid congestion. The current demand for transmission capacity is so large that grid reinforcement cannot promptly alleviate this: the feasibility gap. Congestion is widespread, with most provinces experiencing congestion on both the supply and demand side. This bottleneck threatens housing, industry, and renewable goals. To relieve the pressure on the electrical grid, regulators and industry are seeking fast, localized flexibility. (Multi-carrier) Energy hubs (MCEHs) are often promoted by businesses, grid operators, and public entities as a solution. MCEHs are integrated systems on industrial sites that coordinate power, heat, and possibly hydrogen or other sustainable gasses. Because of the decentralized coordination of energy carriers, MCEHs require less transmission capacity and have, as such, been proposed as an alternative to building grid reinforcement.

However, the evaluation of whether an MCEH can provide beneficial local flexibility is typically assessed through narrow stakeholder business cases or idealized optimization models. Technical models often overlook critical stakeholder decision parameters, such as their business cases and transaction costs, limiting their relevance for practical decision-making. Meanwhile, stakeholder business cases tend to ignore broader system performance, such as societal costs of infrastructure, leading to uninformed decisions and potentially higher societal costs. Therefore, this research will attempt to operationalize the structural societal value to improve decision-making.

The structural societal value of an MCEH in society encompasses a comprehensive assessment of its long-term economic, environmental, and social impacts. This evaluation is crucial for determining the true benefits of energy hubs from a systemic viewpoint when congestion is not the driver. The concept of 'structural societal value' refers to the enduring and wide-ranging benefits an energy hub can bring to society, beyond just relieving congestion.

*This results in the following research question**: What is the structural societal value of a multi-carrier energy hub on an industrial estate?***

The main research question is divided into two sub-questions:
SQ1: What broader societal considerations influence the preference for grid reinforcement or flexibility alternatives?
SQ2: What are the societal costs and benefits of an energy hub as an alternative to grid reinforcement?

SQ1 identifies which factors (e.g., energy cost, reliability, emissions, land use, local participation) matter to stakeholders when comparing the two options. SQ2 then quantifies those factors: calculating the costs and benefits that an MCEH would contribute to society versus the baseline of upgrading the grid. Q1 ensures relevant criteria is captured, SQ2 operationalizes them in an evaluative model.

Research Approach

To evaluate the structural societal value on a deeper level than current techno-economical models do it is required to find a way to quantify societal value. The MKBA, known as societal cost-benefit analysis (maatschappelijke kosten-batenanalyse), reflects this societal value. This multi criteria analysis (MCA) tool is designed to assist policymakers in objectively assessing new projects and making the decision-making process clearer and more comprehensible to external observers. It is particularly useful when a project or initiative has substantial effects on citizens or the environment, when several alternatives exist, and during spatial planning discussions. In the context of this research, the MKBA is therefore a valuable tool to evaluate the societal value of multi-carrier energy hubs compared to grid reinforcement. Figure 1 depicts the methodological interaction where 12 expert interviews determined the evaluation criteria, which were then quantified in a computational energy flow model. To validate this method, the framework is applied in a case study to the industrial estate of Tholen, an already existing hub with grid expansion not expected until 2027 (Stedin, 2024).

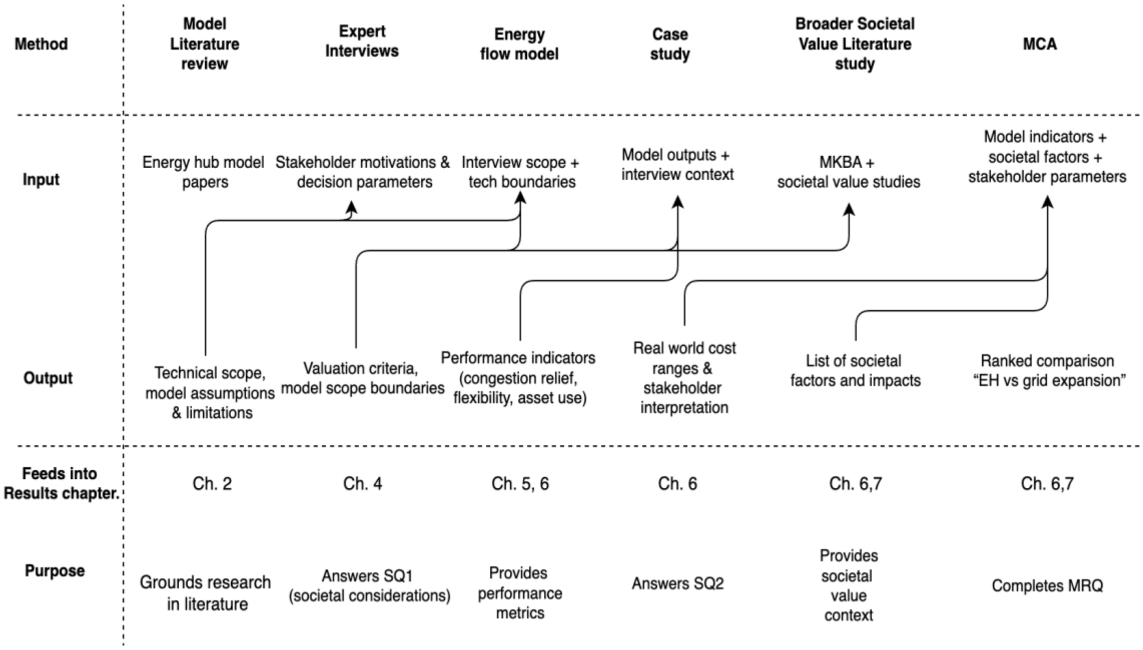

Figure 1, Method and data flow diagram

This figure summarizes the purpose and data source for each methodological step. **Technical model literature** review defines the simulation model's scope and assumptions. **Expert interviews** identify stakeholder decision parameters and acceptable system boundaries. **Energy flow simulation** model quantifies technical interactions (e.g., congestion relief, curtailment, and storage effects) using a custom-built Python simulation and real-world tariff and pricing data. **Case study** application validates and contextualizes the model using real-world data from the Tholen site. **Broader societal literature** adds wider societal concerns for MCA inclusion.

Limitations

Assumptions regarding user behavior and anticipated energy prices introduce elements of uncertainty, while the employment of multi-criteria analysis incorporates subjective aspects. Nonetheless, these issues have been addressed through expert validation and iterative refinement. Although the outcomes of the case study are context-specific, they bolster the assertion that MCEHs provide maximum value under conditions of significant congestion, aligning with the initial observation that MCEHs are primarily utilized for congestion mitigation. Despite these constraints, the research offers a meaningful contribution to understanding the systemic and stakeholder impacts of flexibility measures in energy hubs.

Answer to RQ: The structural societal value of hubs beyond congestion is the ability to provide flexibility for renewable integration

For multicarrier energy hubs on industrial estates to offer structural societal value, they must deliver the location-specific flexibility required to integrate variable renewables. By coordinating local loads, storage, and generation, they can sharpen the dimensioning of network assets and, in specific contexts, postpone or narrow grid reinforcements. Their broader, systemic value is highly context-dependent, hinged critically upon the specifics of the hub, such as load profiles, energy requirements, and local grid constraints. Hubs can thus provide organized flexibility as a structural value. Flexibility can be an expensive method of reducing the required transport capacity. Where the renewable-driven need for flexibility is modest, straightforward grid expansion remains cheaper, simpler, and less risky.

Key contribution: *Evaluating hubs based on their structural value forces decision-makers to consider hubs against grid expansion or other alternatives*

Currently, congestion relief functions as the de facto design criterion, narrowly framing both the purpose and evaluation of hubs. Inclusive criteria that reflect structural societal value shift the focus beyond short-term congestion relief and encourage a long-term perspective on system development. This thus makes the decision between a hub and grid expansion explicit, where it previously was not. The research not only specifies the structural value of hubs but also identifies where the structural value of grid reinforcement lies in comparison.

The interview results show the need to consider various stakeholder perspectives and clarify why hubs are not evaluated for structural value or system efficiency. With the interviews, it was found that grid users prioritized energy access, business case, and supply reliability; grid operators focused on compliance, system efficiency, and long-term management; while government actors emphasized sustainability, economic development, and local politics ambition. These value themes were then grouped and assigned to a criterion that represented an overarching theme and would be operationalized in a similar fashion. These different criteria are presented in Table 1 and reflect the components of structural societal value identified in the analysis, capturing both quantitative benefits and qualitative factors. The operationalization and importance of each criterion depend on the industrial estate and should be used as a guide.

Table 1, MCA criterion table

Priority	Value Theme	Grid Users	Grid Operators	Government Entities	Assigned Criterium	Sum
2	*Technical grid stability/ (Peak) load handling*		3	2	1. Grid-constraint compliance	5
3	*Operational continuity*	3		1	2. Supply reliability / business continuity	4
4	*Local energy resilience*	1	1	1		3
1	*Short-term congestion relief*	3	2	1	3. Congestion/ lack of access to transport costs	6
2	*Supply security*	1	2	2		5
2	*Access to (green) energy*	1	2	2	4. System impact	5
3	*Additionally needed investments*	2	1	1		4
3	*Climate policy contribution*		1	3		4
4	*Reducing grid congestion*		2	1		3
4	*Reputation*	1	1	1		3
4	*Equity and fairness in access*		1	2		3
4	*Societal support*		1	2		3
4	*Effect on labor market*	1		2		3
5	*Flexible grid potential*		2			2
5	*Use of scarce skilled personnel*		2			2
5	*Avoiding grid reinforcement*		2		5. Net annualized system cost	2
2	*Businesscase*	3	2			5
2	*Total Energy cost*	3	1	1	6. Total energy cost	5
4	*Impact on living environment (pollution noise light safety*		1	2	7. Resource footprint	3
5	*Use of scarce materials and impact*		1	1		2
2	*Required land use and spatial planning*	1	2	2	8. Land Use	5
2	*Long-term energy planning*	1	2	2	9. Governance / coordination burden	5
3	*Clear governance structures*	1	2	1		4
3	*Financial clarity and incentives*	2	1	1		4
4	*Collaboration and coordination*	1	1	1		3
4	*Transparency and data sharing*	1	1	1		3

This table categorizes value themes according to the criteria used in the multi-criteria Analysis. Each criterion is defined as follows: **Grid-Constraint Compliance:** Ability to integrate without exceeding existing capacity limits. **Supply Reliability**: Degree of uninterrupted access to energy. **Congestion Cost:** Financial penalty from insufficient transport capacity. **System Impact:** Broader effects on innovation, market structure, and energy transitions. **Net Annualized System Cost:** Combined annualized capital and operating costs. **Total Energy Cost:** Ongoing expenditures for energy consumption. **Resource Footprint:** Environmental and societal impacts of material usage. **Land Use**: Spatial footprint and opportunity cost of occupied land. **Governance & Coordination Burden:** Institutional effort and transaction costs for implementation.

When scoring the value themes on a scale of 1 – nice to have, 2 – important consideration, and 3 – main motive for each stakeholder, short-term congestion relief emerges as the main priority, followed by technical grid considerations for operators and financial aspects for grid users. The government prioritizes contributions to climate policy.

With these criteria, the computational energy flow model was upgraded. The model provided insights into how, where, and when certain flexibility measures depend on the user's load profiles and the transport capacity constraints.
The importance of incorporating these broader societal values into the evaluation criteria of the energy hub was shown by the case study. Contrary to prior expectations, the case study results showed that even when considering structural societal value, the hubs mostly offer valuable breathing

space until reinforcement is delivered. And that this breathing space becomes valuable if the costs of congestion and the delay until reinforcement are significant. In that context, the hub's value lies in mitigating congestion.

Figure 2, which plots the societal system costs over time, shows that in the short term, a hub where both storage and curtailment is favorable, is surpassed by the grid reinforcement in year 6.

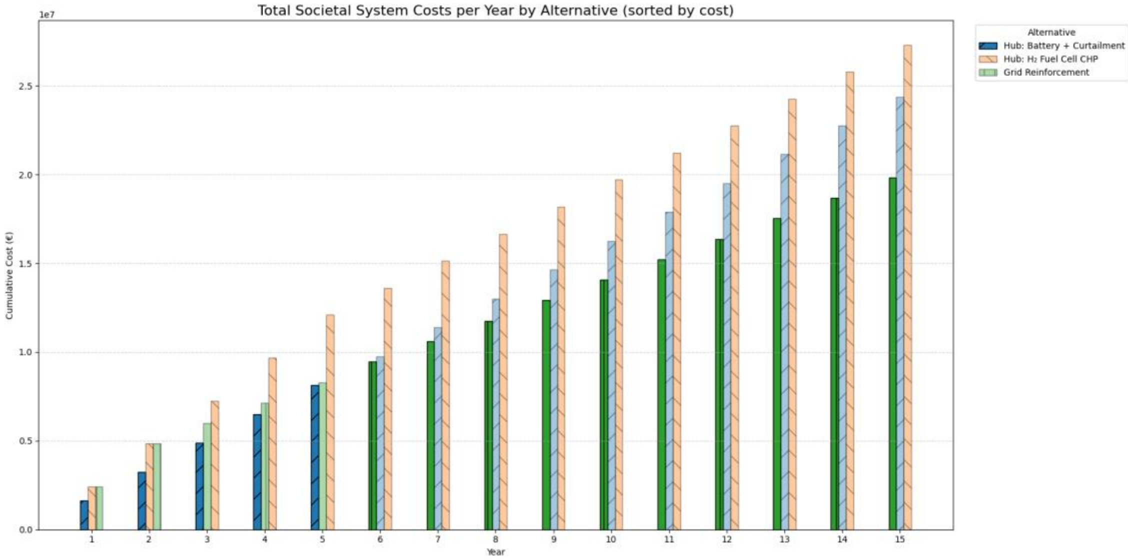

Figure 2, Comparison of societal costs between hub configurations and grid reinforcement

This chart compares the total societal system costs across various energy hub configurations over time. The alternatives featuring battery storage, curtailment, and a fuel cell are presented alongside a grid reinforcement baseline, demonstrating how grid reinforcement will surpass hub configurations in structural value.

The high societal costs of congestion favor any quick solution over inaction or delay, no matter how unattractive this quick solution may be structurally. Fortunately, we can improve upon this, as curtailment has relatively low sunk costs, and electric storage containers have been designed for reuse in other industrial estates. By adopting a dual strategy, as shown in Figure 3, where hubs are initially used and followed by grid reinforcement, we can achieve the lowest societal costs.

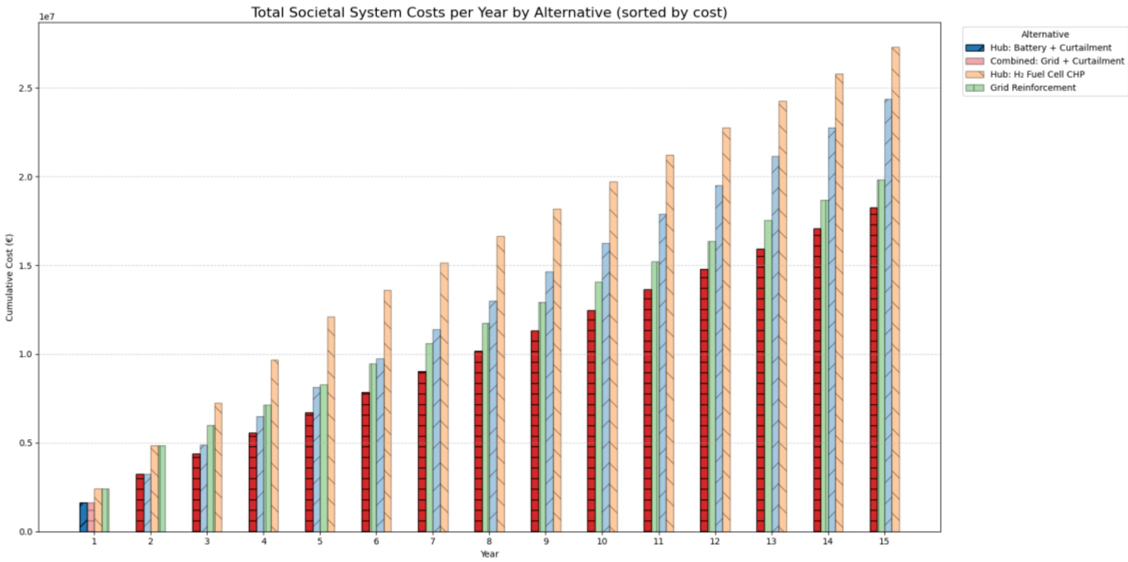

Figure 3, Comparison between hub configurations with the inclusion of a combined strategy

This chart compares total societal system costs across different energy hub configurations over time. Alteratives with battery storage, curtailment, and combined strategies are shown alongside a grid reinforcement baseline, illustrating how combined flexibility options can reduce long-term costs

The case study, however, also demonstrated that including the structural societal value does make an important difference in the decision-making process.
This is because this approach incorporates the total societal costs upfront, making the case for a hub more robust. Once a hub is selected, the assessment clarifies its main value, thus also providing clarity to stakeholders about whether the hub is a temporary or structural solution. By evaluating these values upfront, the choice can be made to design the hub specifically for congestion relief or long-term renewable integration, preventing retrofitting and mismatches, thereby reducing lock-in risks. Even if the ultimate decision is not different, it becomes more informed.

Policy Advice: Choose a Consistent Evaluation Framework

Instead of deciding from the outset whether to opt for a temporary or permanent hub, policymakers should focus on developing a consistent evaluation framework. The favorable path will emerge from the analysis. Based on the evaluation framework, hubs can either be used for short-term congestion relief or as structural building blocks in our energy system. This allows reframing “Is the hub structural or temporary?” into: “Under what circumstances does the hub transition from temporary to structural?**”**

1. **Temporary Hubs: MCEHs are designed** as an affordable interim solution to alleviate local grid congestion until traditional grid reinforcement is in place. These **temporary hubs** provide immediate available capacity to the grid users and are intentionally designed to be phased out or integrated once grid expansion arrives.

2. **Structural Hubs (Long-Term Value):** Investments in MCEHs that are **permanent, structural additions** to the energy system, offering enduring benefits beyond congestion relief. Such hubs facilitate deeper renewable energy integration (e.g., connecting local solar/wind to demand), enhance overall system flexibility (through multi-energy carrier balancing), and eliminate the need for specific grid reinforcements altogether. A structural hub is justified when it demonstrates lasting societal value, meaning its benefits continue even after any pending grid expansions, by contributing to a more resilient and sustainable network.

Action: Reassess Temporary Hubs as Potential Permanent Solutions

If temporary hubs are already built, analyze whether they can deliver lasting value. Temporary “congestion-relief” hubs can become permanent assets, but only if they deliver value beyond short-term grid constraints. Their long-term viability hinges on future load profiles, reinforcement timelines, energy prices, and flexibility needs, factors so uncertain that upfront structural forecasts are unreliable. Instead, any temporary hub should be re-evaluated using a structural societal value framework before planned grid upgrades. This evaluation will confirm whether the hub is still needed once reinforcement arrives and assess its ongoing value, especially its ability to provide flexibility for renewable integration. Because conventional grid reinforcements are usually cheaper and can render hubs redundant, only solutions that support broader system goals warrant conversion into strategic, structural assets. This re-evaluation step ensures that the approach stays flexible and ensures that temporary measures do not inadvertently become long-term fixtures without scrutiny. It also allows for accounting for new policy targets or technological advancements (e.g., improved storage efficiency or hydrogen demand) into the decision.

Conclusion: Make the Trade-offs Transparent and Deliberate

By applying the structural-societal-value framework, the full spectrum of costs and benefits for multi-carrier energy hubs versus conventional grid reinforcement is included, making the trade-offs transparent and deliberate.

It counters current practices of uninformed or narrowly framed decision-making on congestion management and grid reinforcement: for example, it explicitly reveals the inherent trade-off in committing to one solution, and it identifies cases where significant societal value is missed due to a lack of a viable business case.

This is directly policy-relevant, exposing gaps where societal benefits are overlooked under current planning rules. In doing so, the framework becomes a tool for reformulating ambitions among stakeholders and supports the application of consistent criteria for long-term planning of network infrastructure.

Nomenclature

Table 2, Abbreviations

Term	Description
EH	Energy Hub – a local cluster that orchestrates flexible demand, storage and conversion assets to stay within the medium-voltage (MV) grid limits
MCEH	Multi-Carrier Energy Hub – an EH that can convert between electricity, heat, gas or hydrogen to add systemic flexibility
MV	Medium-Voltage distribution ring that forms the system boundary for the study
DSO	Distribution System Operator – owns and operates MV/LV grids; legally barred from energy trading
TSO	Transmission System Operator – national high-voltage grid operator (TenneT in NL)
GTO	Group Transport Agreement – collective contract that pools individual connection capacities inside an EH
ATO	Aansluit- en Transportovereenkomst (ATO)– non-firm ATO contract that permits curtailed use above the agreed capacity
GTV	Gecontracteerd transportvermogen – contracted transport capacity for each participant or group
MCA	Multi-Criteria Analysis – decision tool that integrates model outputs, stakeholder weights and externalities
MKBA	Maatschappelijke Kosten-Batenanalyse – Dutch social cost-benefit framework used to ground MCA criteria
SOC	State of charge - quantifies the remaining capacity available in a battery at a given time expressed as percentage (0% = empty; 100% = full)
CHP	Combined Heat and Power unit that converts gas to simultaneous heat and electricity
COP	Coefficient of Performance – efficiency ratio of a heat-pump; used in grid-reinforcement alternative
"Maakbaarheidsgat"	The feasibility gap between requested and buildable grid capacity in NL planning

SYMBOL	UNIT	DESCRIPTION
E_{AGG}	kW	Aggregated total load at the grid congestion point.
E_{AGG}	kW	Total load of all hub users (participants in the energy hub).
E_{AGG}	kW	Total load of all non-hub users (external loads, fixed demand).

EAC	€/year	Equivalent Annual Cost of an asset.
P	€	Total initial capital investment.
R	–	Discount rate (e.g., 0.03 for 3%).
N	years	Project lifetime.
OPEX	€/year	Annual operating expenditure.
E_t^{CARRIER}	kWh	Energy consumed at time step t for a given energy carrier.
p_t^{CARRIER}	€/kWh	Price per kWh of a given energy carrier at time t.
T	hours	Total number of time steps (typically 8760 for one year).
C_{CURT}:	€	Total curtailment cost.
$E_{\mathrm{CURT,\,I}}$	kWh	Energy curtailed for user i.
$E_{\mathrm{CURT,\,I}}$	€/kWh	Curtailment cost rate for user i.
N	–	Total number of users subject to curtailment.

1 Introduction: Energy Hubs Beyond Congestion Mitigation

The urgency of climate change and the EU's commitment to carbon neutrality by 2050 demand a fundamental shift in the energy system (IPCC, 2023). Electrification and renewable integration are key components of this transition, introducing systemic challenges. Simultaneously, electricity is a critical infrastructure upon which society depends. In the past, where fossil fuels supplemented electricity supply, reliance on carbon-based fuels is being reduced due to their environmental impact (IPCC, 2023, p. 28). These factors are driving significant changes in the energy system, also known as the energy transition (Ministerie van Algemene Zaken, 2024a). This manifests itself in increased electrification, decentralization of energy sources, and a growing reliance on renewable energy. The increasing electricity demands come with challenges, particularly the intermittent nature of renewable energy and its impact on grid reliability ("Nationaal Plan Energiesysteem," 2023,).

One key issue is grid congestion, which occurs when the demand for grid capacity exceeds the available supply at any given time. In this research, congestion refers to the point at which a power line reaches its transportation limit and can no longer accommodate the remaining transport demand, consistent with the definition used in the literature (Van Blijswijk & De Vries, 2012. This limits the ability to transport energy between producers and consumers (*Netcongestie, Flexibiliteit En Opslag Van Energie*, 2024). Congestion may occur on both the supply and demand sides, and in the Netherlands, it has resulted in long waiting lists for increased grid capacity (Stedin, n.d.) (Netbeheer Nederland, n.d.). The need for increased grid capacity far outpaces the ability of grid operators to expand the grid (DNV, 2024). Congestion, like traffic on a road, has ripple effects: when one segment of the grid is overburdened, the stress can shift to adjacent segments, altering usage patterns across the system. The future energy system will become more decentralized due to the distributed nature of renewables (Scholten & Künneke, 2016). However, this shift creates new challenges, including increased congestion and the need for systemic flexibility ("Nationaal Plan Energiesysteem," 2023). This growing disparity between capacity requirements and expansion rates has driven interest in localized solutions that provide flexibility to mitigate congestion (Netbeheer Nederland et al., 2023).

EHs are identified as a potential solution for congestion through system integration ("Nationaal Plan Energiesysteem," 2023). By integrating energy flows within medium-voltage rings, EHs could offer flexibility. Industrial estates provide a unique case study for energy hubs. Unlike smaller consumers, who are legally protected in their energy access, larger capacity users on industrial estates rely on tailored contracts and business cases (Elektriciteitswet 1998, 2003, art. 95a). These estates also represent clearly delineated systems, making them ideal for studying the role of localized flexibility solutions like EHs.

Energy hubs today are mainly focused on congestion mitigation. The hub's success depends on stakeholder cooperation. As a result, the hub effectively becomes a temporary solution, since action is only taken when the congestion problem becomes urgent enough to force cooperation. Consequently, hubs are essentially only deployed reactively. Hubs are not evaluated on their ability to reduce the necessary grid transport capacity or to provide flexibility for intermittent renewables. Although hubs are often cited as capable of reducing grid transport requirements or offering flexibility for renewables like solar and wind, these factors are typically not part of their evaluation.

Currently, decision-making around energy hubs in industrial estates is driven by each individual stakeholder and the specific evaluation method that the stakeholder applies. Because an EH relies on multiple stakeholders, it must align with each of their respective frameworks. These varying, stakeholder-specific perspectives on EHs make it challenging to reach a clear conclusion. Consequently, it becomes difficult to assess the hub against system-wide objectives such as reducing overall energy transport needs or providing flexibility for intermittent renewables.

System integration is intrinsic to energy hubs, meaning that additional systems are introduced, and overall complexity increases. However, when comparing an EH that relies on multiple integrated systems to a simpler alternative such as grid expansion, the scope of evaluation often remains unchanged, as each stakeholder typically focuses only on how the hub affects their own interests. This creates a mismatch: The implications of the added complexity are ignored when they fall outside of the stakeholder's responsibility.

How should an energy hub be evaluated to determine whether it is a viable alternative to grid expansion?

Government policy documents highlight that EHs can enable more decentralized energy systems by locally matching supply and demand, offering flexibility through storage and conversion. Ideally, these systems should uphold public interests (affordability, sustainability, flexibility) while accommodating spatial considerations like housing, business activity, and transportation (RVO, 2025). If solutions to grid congestion can be found, businesses can expand sustainably, more housing can be built, and local stakeholders can gain more control over energy resources. Yet in practice, EHs are rarely judged by these broader public-interest goals. Further, many of these factors, especially those tied to social and environmental outcomes, are challenging to quantify, complicating direct comparisons with simpler solutions like grid expansion.

1.1 Problem Statement: Societal Value is Currently Ignored in Decision-making

EHs are predominantly deployed today as reactive solutions to grid congestion, with limited consideration of their broader potential, specifically, their capacity to reduce grid transport requirements and provide flexibility for intermittent renewables. While EHs inherently involve system integration across multiple energy carriers (electricity, heat, gas, etc.), their valuation typically remains narrow. Traditional assessments often compare EHs to straightforward grid expansion, overlooking the additional systems EHs integrate and the resulting increased complexity and indirect effects. These knowledge gaps lead to the main research question (MRQ):

What is the structural societal value of a multicarrier energy hub in an industrial estate as part of the energy system of the future?

The main research question is divided in two sub-questions (SQ):

> *SQ1: What broader societal considerations influence the preference for grid reinforcement or flexibility alternatives?*
> *SQ2: What are the societal costs and benefits of an energy hub as an alternative to grid reinforcement?*

This research addresses three objectives that stem from these core challenges and are directly linked to the main research question, thereby guiding the direction and scope of the project.

Research Objective 1: Shift the Evaluation Lens

EHs are currently used primarily to solve congestion problems, rather than being assessed for their potential to reduce grid transport capacity or offer flexibility for intermittent renewables. The first objective of this study, therefore, is to examine how EHs can serve the future energy system and enhance overall societal value, rather than merely alleviating congestion. This objective corresponds to the main research question, which explores the structural societal value of EHs in an industrial estate setting.

Research Objective 2: Broaden the evaluation Scope

System integration is integral to EHs and increases overall complexity by adding multiple energy carriers and support systems. However, the valuation scope often remains the same as that used for simpler alternatives, such as grid expansion. The second objective of this study is to expand the evaluation framework to consider these additional systems and any indirect effects they may have on societal value. This objective directly connects to Sub-Question 1, addressing the broader societal considerations that shape the choice between grid reinforcement and flexibility solutions.

Research Objective 3: Clarify Interaction Effects

Finding an optimal balance between transport capacity and flexibility assets is complicated by market imperfections, network effects, and strategic stakeholder behavior. These factors make it difficult to conduct an objective cost assessment and determine the full value of EHs. The third objective is to propose an evaluation method that illuminates how grid capacity and flexibility assets interact, integrating both institutional and technical perspectives so that structural societal value becomes a key criterion in deciding whether an EH is a suitable solution. This aligns with Sub-Question 2, which focuses on the societal costs and benefits of adopting EHs as an alternative to grid expansion.

Academic relevance

1. Expansion of Existing Frameworks: The study advances current decision-making methods for multicarrier energy hubs (MCEHs) by refining how different energy carriers and system elements are evaluated.
2. Institutional–Technical Integration: This research underlines the importance of merging institutional and technical perspectives into a comprehensive assessment framework. The institutional dimension addresses stakeholder-specific contexts, market failures, and decision-making processes. In contrast, the technical dimension defines system boundaries and uses the institutional context to interpret technical constraints and outcomes.
3. Mutual Interdependencies: It highlights interconnections between flexible assets, grid usage, and grid capacity, facilitating more straightforward comparison and clarification for stakeholders.

Societal relevance

1. Justification of Energy Hubs: The research explores the rationale behind establishing an energy hub, shifting attention toward long-term societal value rather than short-term, individual gains.
2. Broader Energy Transition Context: By addressing grid congestion, enabling sustainable economic growth, and accommodating future developments such as housing, the research directly contributes to the wider challenges of the energy transition

1.2 Scope

The scope is limited to medium-voltage rings, where congestion typically occurs at singular points, such as transformer stations (Stedin, 2023, pp. 32–46). While this research analyzes the effects of flexibility solutions within the medium-voltage ring, it does not examine their impact on the high-voltage network. Moreover, its focus is limited to the constrained electricity transport infrastructure and does not account for transport constraints of other energy carriers such as gas or heat.

The EH in this thesis is defined as organized flexibility within the medium-voltage ring, acting as a critical component for mitigating grid transport challenges. Building on this foundation, the MCEH expands the concept by allowing conversion to and from other energy carriers, such as hydrogen (H_2) and heat. In this research, an MCEH typically includes flex assets such as storage, conversion, or demand/supply curtailment that reduce or shift electricity transport requirements. These assets ensure that grid-user needs are met while staying within the grid's operational limits. This study focuses on grid users classified as "grootverbruikers" (large consumers), as they are not guaranteed access to electricity connections under Dutch regulations. These users often have operational flexibility and make investment decisions based on profitability.

Societal value includes the shared costs and benefits of energy infrastructure, including impacts on land use, the business climate, and societal acceptance. The total social, or societal value encompasses all prosperity. It takes a broad view that goes beyond financial and economic wealth, and includes dimensions of prosperity such as health, safety, and the living environment. This is also in line with the definition of value used in the research question. To be more precise, it focuses on the financial and non-financial value concerning the stakeholders with regard to the evaluation of an energy hub. It is assumed that the public entity takes responsibility to protect the public interests, and its position represents the public stakeholders.
In this context**, "structural**" refers to the portion of value that would persist even if congestion were not a driving factor. Any benefit from earlier access to grid capacity due to congestion mitigation does not count toward this structural value. Reduced land or material footprint, lower energy system costs, or accommodating renewables would all be examples of structural societal value.

The future energy system is characterized by decentralized production, integrated intermittent renewables, and enhanced transport capacity to support electrification. As the energy transition progresses, the future energy system must simultaneously meet growing energy demand, integrate intermittent renewables, and advance climate goals. Envisioned as low-carbon and flexible, it aims to accommodate industrial sectors transitioning away from fossil fuels while maintaining reliability. Because solar and wind resources are geographically dispersed, decentralization naturally emerges as a means of achieving the necessary flexibility, rather than decentralization being a goal itself (Scholten & Künneke, 2016). To handle the variability of renewables, the system employs solutions such as energy storage (e.g., batteries or hydrogen), dynamic demand-side management, and energy conversion (Luo et al., 2014; Netbeheer Nederland et al., 2023, p. 9). Although these measures enhance resilience, they also intensify grid congestion issues, as traditional networks were not designed for the bidirectional flows introduced by distributed generation (Buchmann, 2020; Berizzi et al., 2015; Bauknecht et al., 2024).

Flexibility in this research refers to the ability to control either the energy demand or supply. Flexibility is essential to address the challenges posed by renewable energy variability. Assets providing the flexibility are referred to as flex-assets. Examples include energy storage (e.g., batteries or hydrogen), dynamic demand-side management, and energy conversion (Luo et al., 2014 and Netbeheer Nederland et al., 2023). For instance, excess electricity generated during high production periods can be stored and used during times of low renewable output. Similarly, industries can adapt processes to align energy usage with availability. Flexibility in this context is not just a reactive measure but also an opportunity to organize energy flows systematically (Scholten & Künneke, 2016).

1.3 Structure

Chapter 2 presents a literature review relevant to energy hubs where context is given and concepts defined. Chapter 3 introduces the research methodology and methods, explaining how the sub-questions and main research question are addressed. In Chapter 4, insights from the literature review are combined with findings from stakeholder interviews to answer SQ1. Chapter 5 further builds on these findings to build an energy flow model. Chapter 6 applies the insights from the stakeholder interviews and the uses the energy flow model on a case-study in Tholen to fill in an MCA. Finally, chapter 7 discusses the results and 8 provides conclusions drawn from the research, alongside a reflection on the methodology, limitations, and potential implications for future energy system planning and policy.

2 Literature Review and Theoretical Framework

This chapter reviews the literature and builds the theoretical framework for evaluating MCEHs. Section 2.1 introduces the concept of the energy hub as a wicked policy problem in a multi-actor system. Section 2.2 defines MCEHs and explains their interaction with the grid and the broader energy system. Section 2.3 examines how the historical design of the grid constrains current reinforcement options. Section 2.4 identifies key stakeholders and their incentives. Section 2.5 outlines the implicit decision-making logic behind current EH deployment. Section 2.6 reviews existing modeling approaches and exposes the implementation gap between technical optimization and real-world feasibility, forming the basis for the hybrid evaluation framework proposed in Chapter 3.

2.1 Structuring a Wicked Problem: Why There is no Silver Bullet Solution to MCEHs

The Energy Hub is frequently proposed as a solution in the context of integrated energy systems. However, it remains unclear precisely which problem the EH is intended to resolve. This research neither endorses nor dismisses the EH as a definitive solution; rather, it provides a neutral analysis of the outcomes of hub expansion compared to grid expansion. Ultimately, the decision of whether these outcomes justify the construction of an EH rests with relevant decisionmakers. It is important to emphasize that solving congestion issues or optimizing grid expansion are not the primary objectives of this study. The Energy Hub is often proposed as a solution, but its intended purpose must be clarified: What specific problem is it meant to address?

The core issue examined by this research is twofold:

1. The current evaluation framework for EHs promotes their use as a temporary fix for congestion.

2. As a result, it remains unclear whether EHs are a desirable component of the future energy system.

In other words, I argue that the current decision-making framework is not well suited to determine whether hubs should be integrated into the future energy system, posing a risk of unintended adverse outcomes due to the way EHs are evaluated today.

This issue can be understood as a policy problem. For the purposes of this chapter, we adapt a definition from Hoogerwerf (1987) and others. According to this definition, a policy problem exists if two conditions are met:

A Gap Exists: There is a discrepancy between the current or expected situation and a desired criterion (principle or norm).

- Current Situation: It is uncertain whether building EHs will be beneficial in the long term.

- Criterion: EHs should only be constructed if they prove to be advantageous.

A Dilemma Arises: There is an expectation that the gap can be addressed, yet it is unclear how best to proceed.

- Expectation: EHs should only be built if they are indeed desirable, but the challenge is determining when and under what conditions they meet that standard.

A Wicked Multi-Actor Environment

EHs function at the intersection of multiple stakeholders, producers, consumers, transport operators, regulators, each governed by distinct mandates and incentives. Under Dutch unbundling rules, no single company may both generate and transport electricity, so the design, financing, and operation of an EH inherently require coordination among entities with often conflicting objectives. Some actors prioritize reliability and system feasibility (e.g., DSOs seeking to defer costly reinforcement), others focus on cost minimization or return on investment (e.g., large consumers weighing storage capex against avoided connection fees), and still others emphasize environmental or social goals (e.g., municipalities balancing local employment with emissions targets).
This plurality of perspectives transforms EH deployment into a wicked problem (Rittel & Webber, 1973; Waddell, 2016).

Wicked problems are characterized by:

1. **No definitive formulation**: Stakeholders disagree on what “problem” the EH must solve—congestion relief, renewable flexibility, or long-term decarbonization.
2. **No clear solution**: Proposed remedies (e.g., storage, demand response, hydrogen conversion) shift burdens and benefits among actors rather than universally “solving” the issue.
3. **Interdependent sub-problems**: Choices about hub architecture affect business cases, network performance, regulatory compliance, and community acceptance in nonlinear ways.
4. **Evolving requirements**: Changing energy prices, technology costs, and policy targets continually redefine what counts as an acceptable outcome.

Because each actor frames both the problem and acceptable solutions through its own lens, consensus on even the criterion for success remains elusive. Grid operators may demand quantifiable deferral of reinforcement costs; large consumers insist on guaranteed access and minimal operational risk; regulators seek evidence of broader societal benefit; and technology providers require scalable business cases. The field regarding the rules that govern decision making is known as governance. Governance involves the rules governing collective decision-making in environments with multiple actors or organizations, where no single control system can dictate the terms of interactions. Its participants typically used the concept of governance to describe a new pattern of relations between state and civil society (Bevir, 2002). Or as defined by Chhotray and Stoker (2009), governance addresses decision-making structures in contexts where diverse actors must coordinate without hierarchical oversight, which is particularly relevant for multi-EHs. Without a shared evaluation framework, decisions tend to default to the lowest common denominator rather than long-term, system-wide gains.

A governance approach that acknowledges this wicked, multi-actor environment must therefore:

- **Understand stakeholder objectives** and the trade-offs they imply
- **Integrate technical, economic, and institutional analyses** to reveal interaction effects

- **Facilitate transparent negotiation** of acceptable compromises
- **Embed adaptability** to respond as system conditions and actor priorities evolve

Only by explicitly confronting both the multi-actor complexity and the wicked nature of the EH challenge can future evaluation frameworks ensure that hubs contribute enduring structural value rather than serving merely as reactive stopgaps for local congestion.

2.2 How the Multi-EH Interacts with the Grid

Building upon the definition presented in the scope, "organized flexibility in the mv-ring" this section further explores and defines what an EH is and what it can be understood as by the actors.

EHs are localized systems within the electrical grid that provide decentralized flexibility by adjusting energy consumption, generation, or conversion according to system needs. Geidl et al. (2007) describe EHs as units that connect to multiple energy carriers, enabling energy conversion, storage, and supply to meet required services like electricity, heating, and cooling. This concept forms the foundation of EHs as adaptive components of an energy system. While an EH can include multiple energy carriers, this is not a strict requirement. A MCEH extends this principle, incorporating energy hubs capable of energy conversion to optimize system-wide flexibility. For instance, a bakery with ovens powered by both gas and electricity qualifies if its energy input adapts to grid constraints.

"An energy system concept with many local solutions, in which the energy system is kept more balanced at a regional or more specific level, so that less long-distance transport takes place" – translated from II3050"

A practical example of an EH is a greenhouse using a combined heat and power (CHP) unit. The CHP converts gas into heat for the greenhouse and electricity for both the grid and greenhouse. The operation of the CHP adjusts based on the owner's interpretation of system needs. This research, however, focuses on flexibility not as isolated unit but as components influencing the broader energy system in the MV ring. A distinction must be made between energy requirements and grid capacity requirements. Energy requirements reflect the total energy needed within system boundaries, while grid capacity requirements refer to the infrastructure needed to transport that energy. For instance, a solar park may generate sufficient energy for a factory, but if the transmission cable is undersized for peak demand or supply, the factory cannot be powered. Therefore, meeting energy needs within capacity constraints is central to the functionality of EHs.

Intermittency refers to the variable and partially unpredictable output of renewable-energy sources such as solar photovoltaics and wind turbines. Because these sources are weather-dependent, their generation cannot be dispatched at will, complicating the grid operator's obligation to maintain real-time balance between supply and demand (Palovic, 2022). As the share of renewables grows, so does the magnitude and frequency of power swings that must be absorbed by the network.

Grid congestion occurs when the instantaneous demand for transmission or distribution capacity exceeds the physical limit of a line, transformer, or switching component. The first formal congestion warning in the Netherlands was issued in 2011, when newly built power plants exceeded available transport capacity (Van Blijswijk & De Vries, 2012). Subsequent growth in both renewable generation and electrified loads has produced widespread congestion on distribution networks operated by companies such as Liander and Stedin (Netbeheer Nederland, n.d.). When capacity is constrained, distribution system operators curtail new connections or reduce permitted loads, actions that can severely restrict local economic activity (Hadush & Meeus, 2018).

MCEHs address intermittency and congestion by supplying flexibility in grid-capacity use. Technical assets like batteries, electrolyzers, or thermal stores absorb excess energy when line capacity is available and discharge or convert it when the network is stressed. Contractual instruments such as group transport agreements (GTOs) or alternative transport arrangements (ATOs) work by coordinating load-shifting among multiple users. By smoothing renewable output and reducing local peaks, the hub permits more efficient utilization of existing infrastructure and can postpone expensive grid reinforcements.

Figure 4 is a depiction of an EH system relevant to this research, excluding residential houses, as they are omitted due to their limited flexibility options, various limitations, and contract constraints from stakeholder perspectives, which would render this research infeasible. Conceptually, natural gas can be substituted for most other gases, including hydrogen being the main contender.

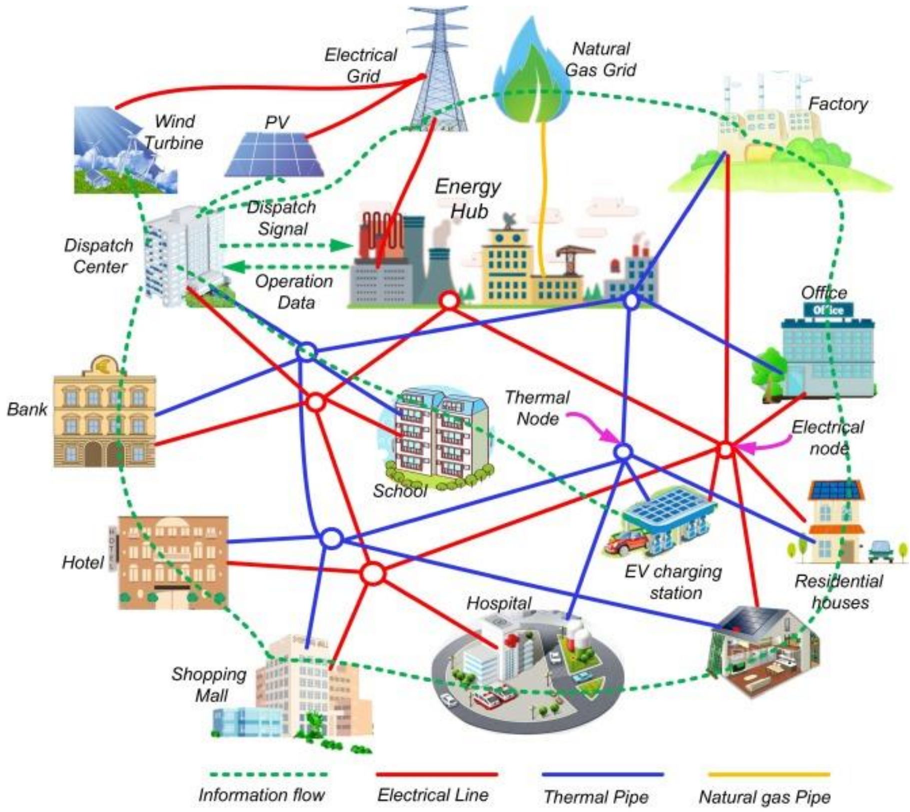

Figure 4, Illustration of a multi-energy system, adapted from Ma et al. (2016)

An Illustration of a multi-energy system integrating various local energy sources (e.g., wind, solar, and natural gas) with interconnected infrastructure for electricity, heat, and gas. The diagram highlights the interplay between diverse urban and industrial users, such as hospitals, factories, residential areas, and data centers, and their connections via electrical lines, thermal pipes, and natural gas pipelines, emphasizing a decentralized and coordinated energy system.

2.2.1 Energy System Integration: Complexity at What Cost?

System integration is defined as:

“Energy Systems Integration (ESI) is an emerging paradigm and at the center of the EU energy debate. ESI takes a holistic view of the electricity, gas, and heat sectors to deliver a clean, reliable, and affordable energy system. By using the synergies within and between sectors, ESI aims to increase flexibility in the energy system, maximize the integration of renewable energy and distributed generation, and reduce environmental impact.” - (Cambini et al., 2020)

Energy system integration involves coordinating components of the energy system, such as generation, distribution, and consumption. This can be on different levels such as national, regional, or local, or the consideration of local resources and demands (Bačeković & Østergaard, 2018). The integration aims to improve upon the efficiency, reliability or other design values of the unintegrated system. Energy system integration does not limit itself to a singular energy carrier, a combined heat and power plant is a classic example. A smart grid is another form of energy system integration (European Commission, n.d.).

While combining systems and increasing efficiency and enabling clean, reliable, and affordable energy may sound like a no-brainer, several barriers hinder the implementation. The most notable barriers for EH’s are the lack of adapted policies and regulation (Cambini et al., 2020). These are manifested in the coordination between grid users and TSO’s, the limited data and access to data and ambiguous regulatory rules.

- **Coordination Challenges Among Grid Users:**
  - Effective ESI requires coordinated action among generators, TSOs, DSOs, retailers, and consumers.
  - Specific challenges include managing increased operational complexity (e.g., with distributed generation and PEVs) and resolving tariff design issues such as decoupling revenue from energy delivery.
- **Limited Data Access and Sharing:**
  - Efficient coordination relies on the seamless flow of data from smart grids and smart meters.
  - Privacy concerns and legal restrictions, along with potential reluctance from DSOs and consumers to share information, hinder data exchange.

- **Ambiguous Regulatory Roles:**
  - Unclear boundaries exist between regulated activities and market operations, especially regarding DSOs’ involvement in new technologies like storage systems and PEV charging infrastructure.
  - Divergent regulatory approaches across European countries further complicate matters.

The proposed efficiency gain from system integration applies to the overall system rather than to each individual participant, whose objectives may conflict. For this gain to be realized, the EH must operate in a specific manner. This stands in clear contrast to the current decision-making process for EHs, which places system performance secondary to congestion relief. Consequently, it remains uncertain whether EHs will indeed enhance overall system performance. Moreover, because each stakeholder primarily considers only their own interests, any parts of the system that fall outside their immediate responsibility remain unaccounted for.

Finally, for an EH to function effectively, seamless coordination is required between grid users and the multiple systems involved. This coordination depends on data and information sharing, as well as on users' willingness to rely on the additional system and conform to its constraints. It also requires the responsible parties to manage the integrated systems, such as a hydrogen network with its suppliers, off-takers, regulatory structures, and pricing models. Companies may be hesitant to share market-sensitive data and may also need to adapt their grid usage to accommodate demand-response programs. Furthermore, incorporating an electrolyzer implies introducing a hydrogen infrastructure, with its own suppliers, customers, regulatory oversight, and pricing structures, which substantially increases overall complexity.

2.2.2 Societal value: The Proposed Evaluation Metric

Determining whether the proposed EH truly constitutes a worthwhile investment requires a careful assessment of its purported performance gains relative to the added complexity it introduces. As discussed in prior sections, performance in this context cannot be captured by a single indicator, such as cost alone, and often encompasses multiple objectives, including economic viability, emissions reduction, and operational flexibility. Additionally, the cost of implementing an EH extends beyond investment and operational expenses, necessitating a broader examination of both direct and indirect costs.

In the case of MCEHs, complexity arises from the need to integrate multiple energy carriers and systems. To evaluate the broader societal benefits of EHs on a structural level, it is crucial to compare all relevant costs and benefits, whether direct or indirect, against feasible alternatives. In the Netherlands, for example, large-scale public investment decisions often employ an MKBA (Maatschappelijke Kosten-Batenanalyse), a policy tool that systematically weighs both financial costs and broader societal impacts (e.g., environmental pollution, health risks, and quality of life) for the national community.

By applying such an evaluative framework, stakeholders can more accurately determine whether the increased complexity of integrating multiple energy streams yields net positive outcomes for society.

The total social, or societal value encompasses all prosperity. It takes a broad view that goes beyond financial and economic wealth, and includes dimensions of prosperity such as health, safety, and the living environment, as depicted in the largest circle of Figure 5 (Planbureau voor de Leefomgeving [PBL] & Centraal Planbureau [CPB], 2022). This is also in line with definition of value used in the research question.

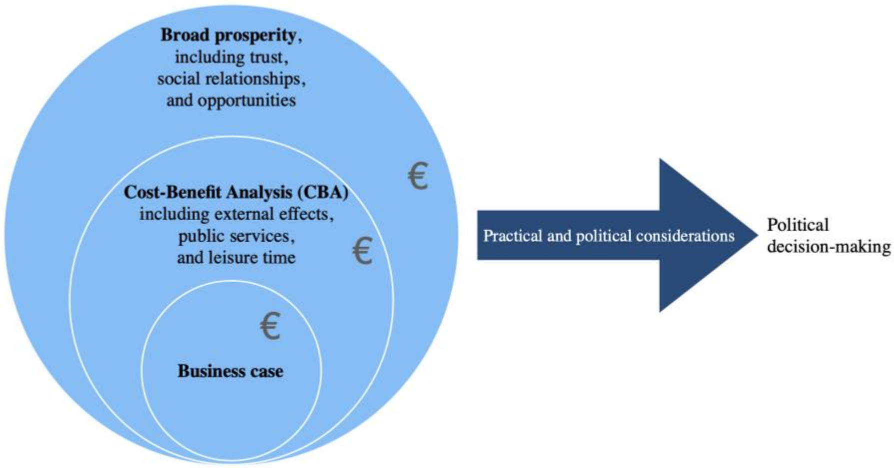

Figure 5, Conceptualization of societal value, adapted from: Planbureau voor de Leefomgeving [PBL] & Centraal Planbureau [CPB], 2022.

Decision-making frameworks can be conceptualized as a layered assessment that influences political decisions. This starts with a narrow business case, then expands to cost-benefit analysis (CBA), which includes societal effects like public services and leisure, and ultimately considers broader prosperity, including trust, social relationships, and opportunity. The diagram shows how practical and political considerations intersect these layers in shaping policy.

This study will focus on the stakeholder's value perception of the energy hub. The stakeholders are the organizations or groups affected by the hub who can influence the outcome. *The value in this research is the sum of financial value, external effects and broad prosperity perceived by the stakeholders*. While it would be ideal to consider every direct and indirect cost and benefit in the decision-making process, many factors such as energy prices and geopolitical events, are highly uncertain. Trying to include every effect can make the analysis impractical, especially when many outcomes cannot be predicted accurately. However, this uncertainty should not justify focusing only on the short-term business case, as many stakeholders and grid users currently do. Instead, it is essential to find a balance between including measurable, relevant factors and acknowledging those that can only be roughly estimated or left out. When data are missing or unclear, this should be clearly noted. The goal is not to achieve a perfect comparison but to provide a well-informed basis for decision-making. The MKBA will be used to substantiate the factors employed in the MCA.

2.3 How the Energy System's History Shapes the Current Approach to Grid Reinforcement and the Value of EHs

Comparing MCEHs with conventional grid reinforcement first demands a clear view of the system they enter, and the reason hubs are used mainly as a congestion "pressure valve," not as a structural design choice. Today's grid reflects decades-old decisions, medium-voltage rings built to an N+1 redundancy standard, and operator incentives that reward "asset-sweating" or lean dimensioning (Scholten, 2016; Verbong & RVO, n.d.). This path dependency constrains future options: reinforcement remains reactive, triggered only once bottlenecks emerge. Up-front savings from squeezing existing assets leave the grid with little headroom, so each new demand spike breeds fresh congestion. Recognizing this cycle is critical before deciding where flexible assets like MCEHs can deliver the most value.

The "feasibility gap," (maakbaarheidsgat) described in the report by Netbeheer Nederland, illustrates this challenge, compounded by the decarbonization and the increased use of renewables. Grid reinforcement alone is not feasible to meet growing energy transport requirements in a timely manner, as depicted in Figure 6. The gap between requested transport capacity and available grid capacity necessitates alternative solutions that introduce flexibility into the system to handle immediate transport demands.

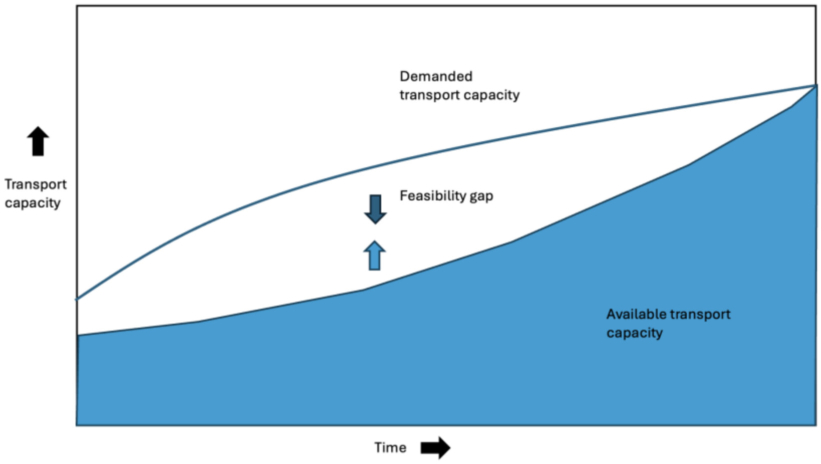

Figure 6, Maakbaarheidsgat, translated from "Eindrapport Maakbaarheidsgat" (DNV, 2024)

Visualizing the "feasibility gap" in infrastructure development. This graph shows the gap between the demand for transportation capacity and the available capacity over time, highlighting a growing mismatch. The feasibility gap points to the part of future capacity needs that current planning and execution speeds can't meet, underscoring the challenges of scaling infrastructure to match energy transition goals.

Flexibility measures, such as energy hubs, offer a solution by addressing localized congestion. From the operator's perspective, these EHs allow for better utilization of existing infrastructure ("beter benutten") and delays the need for extensive grid expansion. From the capacity user's perspective, this means fulfilling their energy requirements sooner. However, these measures come with trade-offs. If used as a design element, they can enable a more intensively utilized grid in the short term. However, if no additional capacity is eventually made available, this approach risks perpetuating congestion, given that the transport requirements are increasing.
Local grid expansion itself is rarely executed in small increments. Instead, reinforcement typically involves replacing a lower-voltage line with a higher-voltage one, constructing new transformer stations, or building additional lines. Substations and cables are available in standard sizes and capacities rather than being tailored to exact peak demand, leaving surplus capacity available for a time after an upgrade. In contrast, flexibility measures are often designed for a specific use case, providing additional capacity only to users who actively participate in the hub.

In the Netherlands, a decision was made to construct ring-shaped electricity grids. The N-1 contingency standard that arose from this philosophy, according to Verbong, illustrates how past technical choices continue to shape the present. In the case of the feasibility gap, where grid reinforcement alone cannot promptly meet transport demands, flexibility measures are suggested as a solution. However, these flexibility measures will still affect the system even after the gap has been closed. This raises the question of what the desired design direction is regarding flexible assets. Operators typically see a permanent role for EHs, viewing flexibility as part of the future energy system. Users, however, often perceive the EHs as a temporary solution to sustain their operations until the grid is sufficiently reinforced.

Figure 7 is an example of the interplay between the use of flexibility and grid reinforcement to tackle the capacity issues. If the requested transport capacity is addressed using flexible assets, the required flexibility will first increase and then decrease until grid reinforcement is sufficient. If grid reinforcement continues to be the primary focus without change, this flexibility, or grid reinforcement, will eventually become unnecessary, assuming the predicted transport capacity demand is correct.

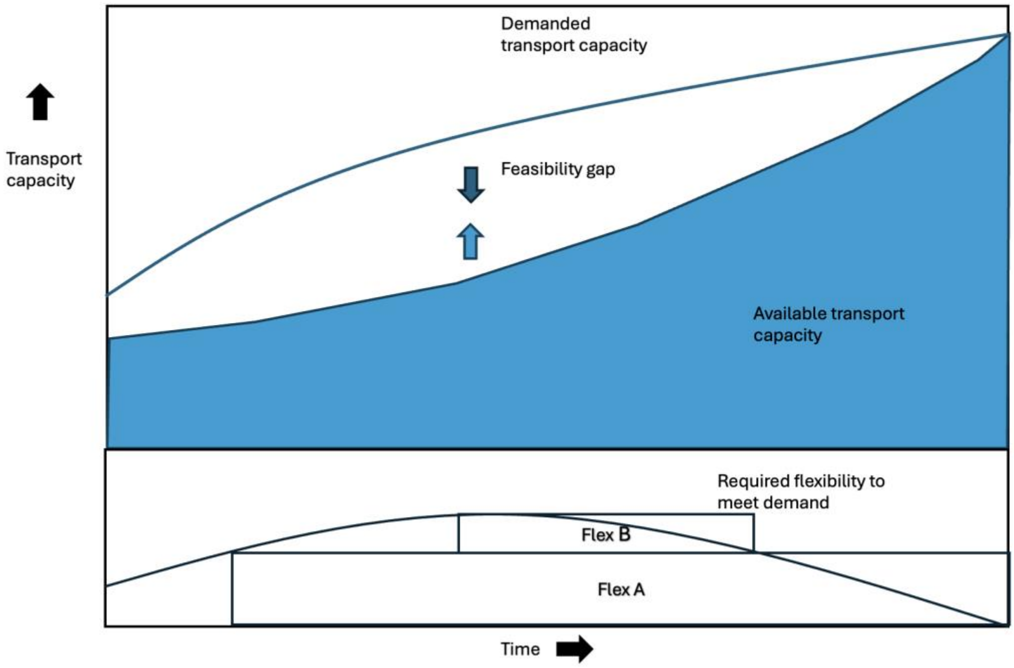

Figure 7. Feasibility Gap with example flexibility, adapted (DNV, 2024)

The feasibility gap arises when the growth in demanded transport capacity outpaces the increase in available capacity. The bottom panel illustrates how different flexibility solutions (e.g., Plan A and Plan B) might contribute to bridging this gap.

The interaction between infrastructure and external factors further complicates grid reinforcement decisions. For example, limited grid capacity has already driven business relocations to areas where capacity is more readily available and is a direct reflection of how infrastructure influences the broader environment (Li et al., 2021). The interaction between available grid capacity and required grid capacity is omitted for simplicity's sake, but it is likely that they dynamically influence each other (does supply create demand? Or does demand create supply?). -If there is a surplus of grid capacity, it is likely that it attracts large capacity users, reducing the surplus in capacity. Congestion is thus not solely a dimensioning issue; balancing and regulatory capacity are integral parts of the problem (De Laurentis, 2022).

The port of Rotterdam is a good example of the complex multifaceted challenge known as grid reinforcement. The port faces unique challenges due to its energy and fossil-fuel-intensive industry, which in turn results in congestion. To protect the interests of the stakeholders of the port, a specific taskforce has been setup, underlining the interaction between (un)available grid capacity and multi stakeholder driven mitigation actions, including the operator, capacity user and governments (New Energy Taskforce to Support with Tackling Grid Congestion in the Port of Rotterdam, 2024).

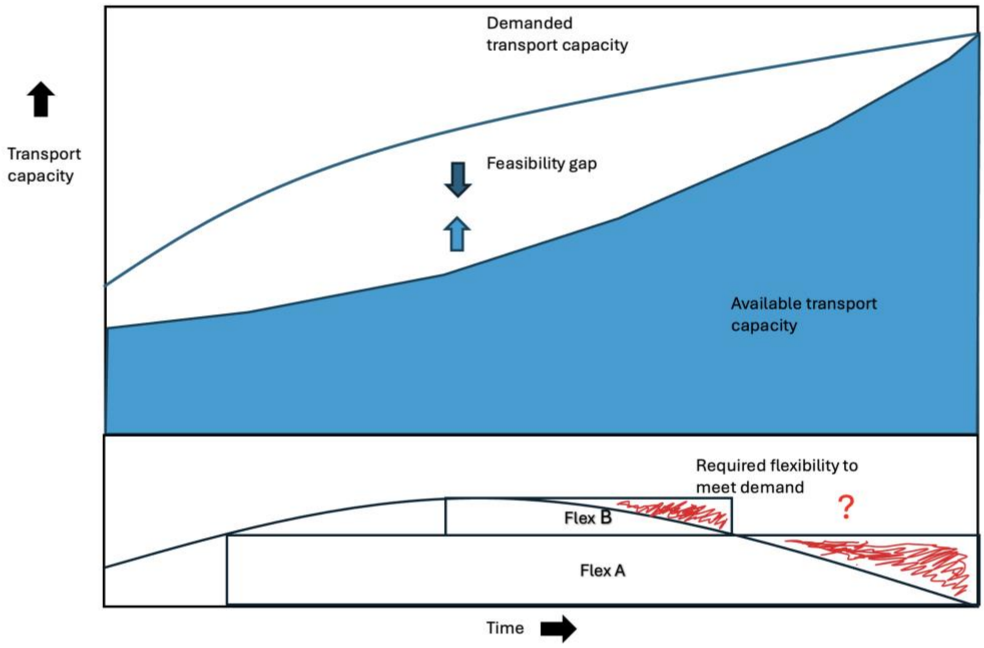

Figure 8. Feasibility Gap, adapted from (DNV, 2024), hypothesis: EH represents structural value

The feasibility gap (top) reflects the structural mismatch between available and demanded transport capacity. The hypothesis is that Energy Hubs could offer structural value by contributing to this required flexibility. The bottom panel illustrates the flexibility required to bridge this gap, with uncertainty around what its use is when the feasibility gap fades.

Figure 8 depicts the essence: if aligning available transport capacity with requested capacity becomes the guiding principle, stakeholders must ultimately choose between phasing out existing flexible assets or forgoing grid reinforcement entirely. In both cases, the transport demand is met, but the decision becomes a fundamental design choice. This design decision, striking an optimal balance between grid flexibility and reinforcement, is ultimately shaped by stakeholders' visions and reflects their diverse requirements and perspectives on the future energy system.

2.4 Who's Incentivized to Participate? Who are the Primary Stakeholders?

The participants and their perspectives must be understood to further understand the context in which the evaluation design challenge takes place. Based on the definition of an Energy Hub presented in the previous section, certain components are indispensable for its operation. At its broadest, an EH can be seen as part of an energy system that incorporates flexibility measures. To constitute an energy system, at least three fundamental elements are required:

1. Energy Demand – The need for energy by users or processes.
2. Energy Supply – The availability of energy from sources such as renewables, fossil fuels, or grid connections.
3. Energy Transport – The infrastructure and capacity to move energy from supply points to where it is needed.

Flexibility, the ability to shift energy demand or supply, can be achieved in two ways:

1. Assets – Through energy storage or conversion systems.

2. Grid Users – By incentivizing or regulating flexible energy consumption or supply. This requires appropriate incentives or obligations to motivate participation.

The key stakeholders in an EH include at least the following: an energy-consuming or energy-producing party, a party providing flexibility, the entity responsible for energy transportation, and a regulatory body. Under Dutch law, grid operators, responsible for energy transport are prohibited from simultaneously transporting and supplying, ensuring a clear separation of roles.

The regulatory body, typically a government authority, defines the rules of the system, establishing the legislative framework within which all parties must operate. While the roles of the government and grid operators are clearly defined, the remaining grid-using party has significant freedom in the role they can take on. This party can freely choose to consume energy, supply it, provide flexibility, or any combination of these based on their own objectives and needs within the system's constraints.

The stakeholders can thus be categorized according to the following categories:

1. Companies representing the grid user
2. The grid operator
3. Governmental entity representing local regulation and interest.

Addressing congestion and reinforcing the grid depend on the coordinated actions of multiple stakeholders, each with its own agenda and incentives.

2.4.1 The Grid Operator

Distribution System Operators, or DSOs, engage with EHs to provide grid users with alternatives when they face congestion because EHs can potentially lead to a better-utilized electricity grid.
The main responsibilities of a grid operator are maintaining grid affordability and ensuring security of supply. Their primary task is to provide electricity consumers with sufficient transport capacity, a responsibility complicated by increasing electricity demand, workforce shortages, and spatial limitations for grid expansion.

Given the current grid congestion, the anticipated increase in electricity demand, and the limited ability to expand the grid in a timely manner. Grid operators view energy hubs as a potential solution for offering perspective to users when timely grid connections are not feasible. Furthermore, they can simplify the contractual part of flexibility, as the users within the hub would coordinate their energy use among themselves, instead of the operator acting as an intermediary. Grid operators play a facilitating role in the development of energy hubs. For example, Alliander, through its subsidiary Firan, supports initiatives that facilitate local energy solutions, including EHs (Firan, 2025). This approach helps manage grid capacity more efficiently, providing alternatives when physical reinforcements are not immediately feasible. This makes some EH’s on particularly desirable if it can address an important bottleneck.

However, not all operators are able to fulfill their connection tasks, and approaches to energy hubs vary among operators, likely due to differences in the severity of congestion issues and their own strategy. Operators with more significant challenges tend to take more proactive measures. For example, Alliander supports initiatives through Firan, where the grid operator facilitates energy hub development despite this task formally falling outside its role (Firan, 2025). This approach is seen as beneficial in addressing connection challenges and congestion issues.

Additionally, TenneT evaluates grid capacity based on the summation of individual companies load profiles. EH's change the load profiles of said companies making it unclear whether energy hubs at the medium voltage level help mitigate or exacerbate TSO-level congestion problems. From the perspective of the grid operator, systemic priorities such as supply security and affordability outweigh individual connection tasks due to their societal importance. Grid operators feel a duty to participate in EHs to provide businesses with viable options in the event of congestion. They also explore the alternative tasks EHs could solve for them. However, the exact benefits of EHs for grid operators are not yet clear, which, combined with their risk-averse behavior, leads to a strong focus on potential obstacles. The highly technical and complex nature of this issue makes it difficult and time-intensive to support capacity users in the EH process, particularly when the benefits for the grid are uncertain. Nevertheless, at the TSO level, EHs seem to be gaining traction as an increasingly attractive and significant component of the future energy system, as suggested by the visions of Enexis and Alliander.

From a public goods perspective, grid operators manage a natural monopoly (the transmission/distribution network) that must be heavily regulated to ensure universal access. Their incentives align partially with social welfare objectives (e.g., affordability, reliability) but are also shaped by regulatory frameworks that encourage or discourage investments in new solutions such as EHs.

2.4.2 Grid Capacity Users

Large consumers, particularly those located in industrial estates, significantly influence grid demand. Their cooperation is typically reactive, often contingent on experiencing direct impacts from congestion. This reactivity limits the opportunity for preemptive, system-wide solutions. Organizations like VNO-NCW and MKB-Nederland advocate for clear policies and fair pricing, ensuring that businesses are not overburdened by the costs of grid expansion (VNO-NCW, n.d.).

A distinction must be made between large consumers and large industrial users. SMEs often fall into the category of large consumers but frequently lack the size and energy management expertise seen in energy-intensive industries. Variability in expertise is industry-dependent; while certain sectors possess the knowledge to address energy challenges, many SMEs struggle with limited resources and understanding.

Despite growing recognition of grid congestion, many businesses remain unaware of its implications until directly impacted. For example, electrification plans aimed at sustainability or business growth may overlook grid constraints, leading to unfeasible projects. Companies purchasing electric vehicles may find themselves unable to install charging stations due to congestion, highlighting a mismatch between ambition and grid capacity.

Nonetheless, some businesses view EHs as opportunities rather than constraints. Greenhouse operators utilizing CHP systems or companies in process technology often leverage their expertise to stay informed and proactive about energy management. These businesses recognize EHs as tools to address acute congestion issues, enhance operational efficiency, reduce CO_2 emissions, and secure energy reliability.

In summary, businesses are key stakeholders in EHs as direct users and beneficiaries. For many, EHs represent solutions to immediate congestion challenges, while others view them as opportunities to innovate, optimize operations, or generate revenue through participation in energy or capacity markets. Businesses primarily evaluate EHs through the lens of maintaining continuity and seizing potential economic benefits.

Capacity users generally act as rational economic agents, focusing on cost-benefit analyses and profit maximization. From a transaction cost perspective, they weigh the administrative or contractual complexities of EHs against expected returns (e.g., improved resilience, short-term congestion relief). Different users have heterogeneous preferences and resource levels, which influences how quickly they adopt new solutions.

2.4.3 The Governmental Entity

Governmental entities, such as municipalities and provinces, have less direct interest in Energy Hubs than other stakeholders. They typically become involved because they view EHs as tools to prevent grid congestion, which can adversely affect businesses within their jurisdictions. Figure 9 details the various levels of government involved.

EHs are mentioned in national, municipal, and provincial policies, highlighting their potential contributions to energy and climate objectives. Municipalities and provinces have an indirect interest in supporting local businesses and employment, and EHs can aid in achieving these goals. Their involvement in EH projects varies as they may act as initiators, mediators, or sometimes remain uninvolved. However, since EHs are custom solutions, they do not always guarantee the prevention of grid congestion or effectively accommodate companies' electricity usage.

Municipalities perceive EHs as solutions to local problems, using municipal boundaries as natural delimitations. However, these boundaries may not align with where capacity issues occur. For example, the A1 business park in Deventer spans areas serviced by two different grid operators: Alliander and Enexis. This means a municipality might propose a solution, such as a specific EH, without fully understanding its impact on the broader electricity grid. Consequently, companies and municipalities may invest time in explorations that lead to incorrect expectations.

At the national level, the Ministry of Economic Affairs supports regional development agencies (ROMs) that are involved in the development and support of companies. Some of these agencies, such as Oost NL and Horizon Flevoland, are actively engaged in the development of (smart) EHs.

Governments act to rectify market failures (e.g., externalities of congestion, universal access requirements) and promote the public interest. They influence EH feasibility through policy instruments (incentives, mandates, funding) and aim to balance private sector innovation with societal objectives (e.g., emission targets, economic development).

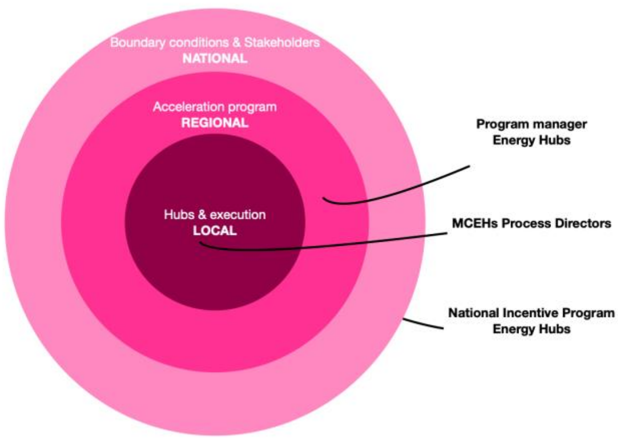

Figure 9, Division of public roles within smart energy hubs, translated from (smart energy hubs, n.d)

Visualization of the multi-level governance structure in Smart Energy Hubs (SEHs), showing how responsibilities are distributed across local, regional, and national levels. The local level focuses on hub development and execution, supported by regional acceleration programs and embedded within national boundary conditions and stakeholder frameworks.

The division of roles in bullet points

- **Grid Users:** Large energy consumers, especially in industrial estates, rely on energy access for their operation and exert significant pressure on the grid. Their participation in solutions like energy hubs often hinges on the direct benefits to their operations or the mitigation of risks.
- **Grid Operators:** Tasked with maintaining balance and transporting electricity, operators are increasingly turning to flex assets like energy hubs to provide their services under capacity constraints.
- **Governments:** By setting policy and regulatory frameworks, governments influence the system's design and enforce alignment with societal objectives, such as decarbonization and affordability.

2.5 Current Practice: The Implicit Stakeholder Evaluation of Energy Hubs

Although no explicit evaluation framework systematically assesses whether to construct an EH, an implicit general approach is commonly used. As previously noted, the primary consideration for developing a hub is its ability to alleviate congestion, rather than enhancing overall system efficiency or performance. [1]

Example of the stakeholder decision-making process in action

Consider a data center that requires additional grid capacity to expand its operations. Although growth in demand would increase revenue, the data center faces a four-year wait for additional capacity through conventional grid reinforcement. Calculations reveal that purchasing an energy storage unit independently would not be cost-effective and, moreover, would fail to resolve the center's main challenge. Because the data center's load remains relatively steady, there is insufficient transport capacity to allow the storage system to recharge effectively.

Another company on the same MV ring also aims to expand, though it exhibits a more variable consumption profile. By coordinating their efforts and investing jointly in electrical storage, both companies could potentially secure the energy capacity they need more quickly, thereby supporting their growth. However, consultation with the grid operator reveals that the companies' initial projections were overly optimistic. They assumed they could simply aggregate their individual contracted transport capacities to form a new, combined GTV.

The operator, however, warns that the MV ring is overburdened and will grant this aggregated capacity only under the condition that consumption be curtailed during specific hours.

The second company, whose willingness to pay is lower than that of the data center, reluctantly agrees to proceed. Because the data center cannot significantly modify its load, it bears the brunt of usage restrictions, effectively conceding to ensure the partnership remains viable. This scenario illustrates how, in practice, the implicit approach to Energy Hub development often centers on congestion relief, shared costs, and the willingness of multiple stakeholders to participate under constrained operational conditions.

The following steps can be identified in the stakeholder decision-making process, detailed in the above example:

1) Can an EH effectively resolve the immediate (acute) problem?
2) Is the issue sufficiently critical that consumers are willing to incur significant costs to maintain energy access?
3) Does the anticipated duration of grid reinforcement preclude it from being considered a viable alternative?
4) Are all critical actors (i.e., those essential to the hub's realization) sufficiently invested or dependent on its success such that they will not impede the process?

If these questions are all answered affirmatively, the planning and operation of the hub typically proceeds.

How much are you willing to pay?

At the core of evaluation is the concept of value. From a utilitarian perspective, increasing value is considered desirable. This principle drives decision-making among stakeholders, as an EH must align with their perception of value to be viable.

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[1] [1] Energy hubs that boost overall efficiency already operate in practice, unlike the hubs analyzed here, they are privately built and run, and they are not designed to enhance grid stability. A typical example comes from the process industries, where vertically integrated chemical complexes in the oil sector interlink chemical and energy flows to optimize plant performance.

For businesses, this value perception often translates into a business model or business case. A business case encapsulates the rationale behind engaging in or initiating a project or task. In the context of this research, it denotes the considerations that validate participation from the perspective of each individual actor. The decision of whether to participate or not for each actor is presumed to hinge upon their respective business case, which is inherently tailored to each actor's unique circumstances.

The implicit approach described above, where stakeholders primarily weigh a hub's effectiveness in mitigating congestion and determine who will pay, naturally extends to the notion of each actor's business case. The applied definition of a business model is understanding the conceptual frameworks of business logic held by managers, rather than describing reality (Massa et al., 2017). The business case is not limited to direct financial value. While the collective decision to move forward with an Energy Hub is driven by a handful of questions, each participating entity arrives at that decision based on its own cost-benefit calculations, financial constraints, and operational flexibility. In other words, the success of any EH initiative ultimately hinges on whether it makes sense for every stakeholder from a business perspective. The data center, for instance, will evaluate how soon it can secure additional capacity and whether that timeframe justifies the expense, whereas another company on the same MV ring will compare the flexibility gains with the project's overall financial viability. Consequently, if these actors do not foresee sufficient returns, whether measured in profit, operational resilience, or grid access, they have little reason to engage, regardless of whether the EH itself seems beneficial at a system-wide level. This underscores that the implicit framework outlined previously is intertwined with each actor's business model. Actors join or drop out of an EH project based on individualized assessments of risk, reward, and opportunity costs, all of which form the foundation of their respective business cases.

Why congestion is not a market-failure problem

The electricity grid cannot be treated as a competitive market because its transport capacity is tied to specific locations, allocated administratively on a first-come, first-served basis, and paid for through socialized, regulated tariffs. Consequently, the price of grid capacity fails to capture its full societal value, so capacity cannot shift to users with a higher willingness to pay. Because prices neither vary with scarcity nor allow trading between users, congestion reflects deliberate policy choices that prioritize reliability and equity. Flexibility assets do respond to supply-and-demand signals, yet traditional grid services remain monopoly-regulated and non-tradable. Entities without direct financial incentives such as governments, local communities, or regulated utilities, still require a structured approach to decision-making. While their motivations may not be monetary, their interests are safeguarded based on their perceived value. When assessing an EH from an actor's perspective, there must be a compelling value proposition that justifies their participation, financial or otherwise. The following literature review will explore the explicit, model-based evaluation method, compare this with the implicit stakeholder decision-making process and argue the incompatibility between both.

2.6 Model Literature Review

This literature review aims to gain an insight in current modelling approaches of EHs and to understand their advantages and limitations. The previous section discussed the implicit evaluation method currently used for energy hubs. In addition to these implicit methods, there are also attempts

to evaluate hubs more explicitly through models. Typically, such models aim to measure the (system) performance of an energy hub, using simplified representations of reality. Because these models focus on potential system improvements, they adopt a system-level perspective as their analytical scope. However, most existing models rely on optimization to compare monetary outcomes across different alternatives. To facilitate these comparisons, the models must quantify specific outputs, which inevitably limits them to the parameters they can measure. As a result, transaction costs are often omitted, leading to overly optimistic performance projections. Moreover, these models frequently ignore interaction effects among multiple transport capacity users on the same MV ring, even though such interdependencies are crucial; do their peaks coincide? Are they willing to share their usage data? Likewise, societal impacts are rarely incorporated, largely because they are difficult to quantify, thus overlooking broader, long-term consequences beyond direct monetary considerations.
The method and approach are detailed in Appendix A.

2.6.1 Findings

A general approach was identified in the modeling of multi-source or carrier energy system research papers. This approach consists of the following steps:

1. Initially, it was recognized that the existing energy system requires adaptation as it is deemed inadequate to meet both present and future demands.
2. Secondly, a mechanism through which the energy system could be improved was hypothesized, examples include solutions aimed at handling the intermittency of renewables through energy storage or the diversification of energy carriers.
3. Following this, the presentation of a cost function was noted. Typically, this encompasses capital expenses, operational costs, or investment expenditures.
4. Ultimately, it was concluded that combining energy sources or carriers can lead to various improvements, such as reduced costs, enhanced grid stability, or decreased emissions.

However, only 6 of the 22 studies noted the need for some form of coordination or sociotechnical parameters, with exceptions like Wang et al. (2023) who incorporated sociotechnical parameters, such as transaction costs, or considerations for actor roles as seen in Bollinger et al. (2016). Fan et al. (2023) did however propose a virtual peer-to-peer trading solution, optimizing according to Information Gap Theory.

A limitation of these studies, as concluded by Fattahi et al., is that low-carbon energy systems modeling rarely includes sociotechnical factors such as energy policy harmonization, energy market design, business models of new technologies, legislation and legal aspects of the energy transition, and social acceptance implications of the energy transition (2020). The implementation of such optimization models often has multiple interdependencies (Gürsan et al., 2024, Wang et al., 2023, 2022, Gusain et al., 2022). Not acknowledging these, limits or hinder the implementation of such models, which begs the question if the models are fit for purpose or if their reduction of the social aspect from the sociotechnical cripples their usefulness when it comes to implementation. The social dimension was beyond the scope of most of the technical or economic models, as it is handled as an afterthought. The notion that coordination is essential is at the forefront of the work by Gürsan et al., (2024) and Wang et al., (2023), and underwritten by Bollinger et al., who argue for a growing importance for the link between the social and technical dimensions of the electricity infrastructure.

Despite recognizing the potential benefits of combining energy sources or carriers, studies often overlook the importance of coordination for implementing proposed solutions. This gap hampers the usefulness of optimization models, as they fail to capture real-world trade-offs and interdependencies, thereby limiting their effectiveness in guiding energy system transitions.

2.6.2 Why Technical Models are of Little Use For Decision Making: The Model Implementation Gap

Most techno-economic optimization models of energy hubs are built to prove technical potential, not to guide real investment decisions. Consequently, they seldom replicate the evaluation sequence that actual stakeholders follow when deciding whether to join or finance a hub. Two problems arise:

- **Different solution spaces.** In a model, the “optimal” design is determined by a cost or emission objective under a fixed set of assumptions. Each actor applies its own constraints, such as transaction costs, risk tolerance, and regulatory deadlines. Those constraints can eliminate many of the model’s preferred options. The space of feasible solutions is therefore much smaller for stakeholders than for the model.

- **Absent decision logic.** Technical models treat participation as a given; they do not simulate the negotiations, cost-sharing rules, or governance structures that ultimately determine whether a hub is built. An elegant optimum on paper may thus be politically or commercially impossible.

The result is an implementation gap. Models promise what could happen under idealized conditions, while actors must choose among what can happen given their specific constraints. The models often fail to capture the realistic evaluation process that stakeholders undergo when deciding whether to develop or participate in an EH. This results in a fundamental mismatch between what models suggest as optimal and what actors perceive as viable alternatives. In other words, the solution space is constrained differently when approached from a stakeholder perspective than when using the model perspective. As a result, current models, despite not being decision-making tools, often create an unrealistic promise of "what could theoretically happen under numerous assumptions, while ignoring stakeholder behavior." This idealized and optimized vision is then misinterpreted as a viable target, regardless of its practical feasibility. This could explain why EHs are frequently proposed as solutions to a wide range of energy system challenges, despite significant uncertainties regarding their real-world implementation. Governments add a further layer, because they must weigh energy equity and security alongside technical feasibility, dimensions rarely captured in optimization runs. For these reasons, the present research abandons a search for a single optimum.

Instead, it combines stakeholder interviews, a non-optimizing simulation that exposes interaction effects, and a Multi-Criteria Analysis that weighs both private and societal impacts. This approach places the decision process itself at the center of the evaluation, reducing the risk that premature optimization will hinder practical implementation.

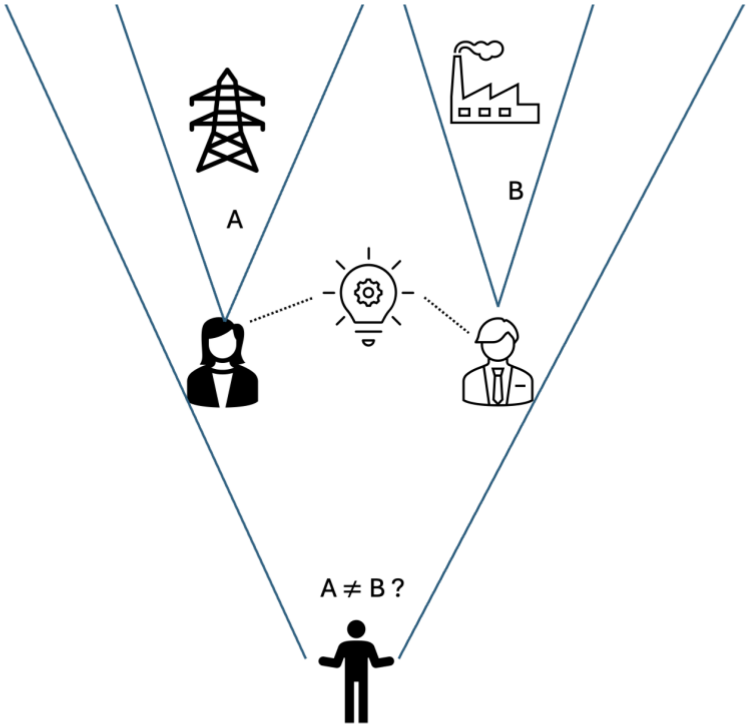

Figure 10, Stakeholder perspectives

Different stakeholders recognize problems in the energy system and look to Energy Hubs (EHs) as a solution, but each envisions a different problem and a different version of the EH. While actors A and B agree to implement an EH, observer C questions whether they're aligned in their understanding.

2.6.3 Conclusion: How have Hubs Been Evaluated?

Economic and technical models serve as simplified representations of reality, shaped by the utility functions or investment returns. However, energy hubs are not purely technical solutions; they are socio-technical systems that aim to address challenges in both technical and institutional dimensions.

The literature review reveals that while technical modeling of energy systems is abundant, its connection to real-world decision-making remains somewhat limited. Most models rely on some form of optimization, either from the perspective of a single stakeholder or as a system-wide optimization problem. Typical approaches include cost-minimization strategies (e.g., "cheapest to run under condition X") or multi-objective optimization models, where different system configurations are compared.

Figure 11 illustrates a simplified schematic of the current **implicit stakeholder evaluation framework** for developing an energy hub. Each actor independently assesses whether the hub's value proposition is sufficiently appealing.

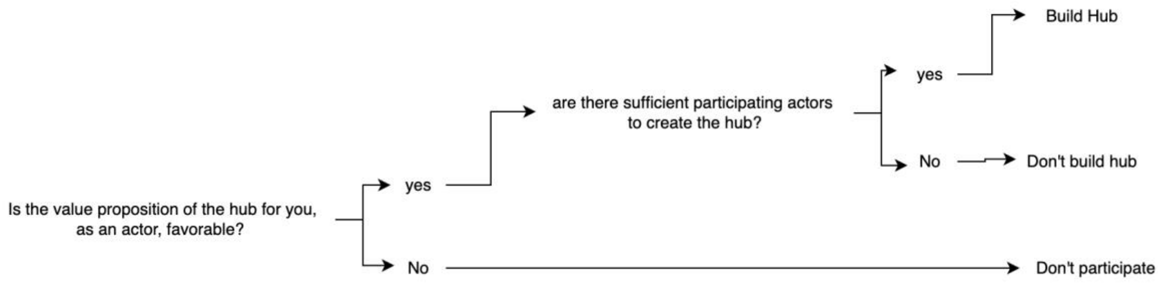

Figure 11, Decision tree depicting implicit stakeholder evaluation framework

This diagram illustrates the implicit decision-making process stakeholders may follow when considering participation in an energy hub. The first decision node assesses whether the value proposition is favorable to the actor. If so, the next step evaluates whether sufficient participating actors are available to realize the hub. Depending on the outcome, stakeholders may decide to build the hub, not build the hub, or not participate

If an actor deems the hub insufficiently valuable, they simply opt out. Once the required minimum number of actors perceives adequate value, however they choose to define it, they collaborate to build the hub. This approach focuses on feasibility and actor interests while disregarding factors beyond the stakeholders' immediate scope. As a result, externalities that impose significant costs on non-participants are not necessarily accounted for. However, unlike the technical model, all costs incurred by the actor, be it direct or indirect such as transaction costs, are factored and quantified by them. While estimating the true value of a hub to a company may pose a significant challenge, it represents the perceived value of the hub to the actor's best ability and serves as their decision-making basis.

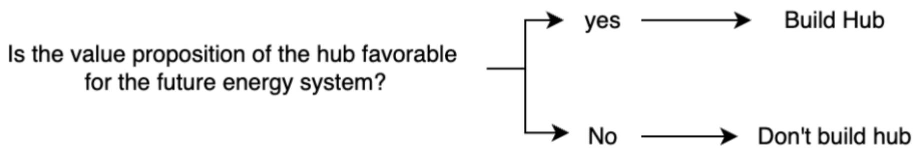

Figure 12, decision tree depicting decision framework based on technical models

This simplified decision tree outlines a system-level evaluation approach for energy hubs grounded in technical modeling. The central question assesses whether the value proposition of the hub is favorable for the future energy system. If the answer is yes, the recommendation is to build the hub; if not, the conclusion is not to build the hub. This framework reflects a more top-down, model-driven rationale, focusing on systemic rather than actor-specific benefits.

By contrast, a more holistic approach, usually taken by the **technical modelling approach** depicted in Figure 12, would ask whether the hub is beneficial for the future energy system overall. However, answering this question is inherently challenging, as the definition of "beneficial" varies by stakeholder. Even if the hub is deemed desirable, subsequent issues remain unresolved, including how costs and benefits should be shared and precisely what "desirable" entails in the broader energy-system context. Moreover, even a clear answer to these questions does not ensure that all necessary actors will cooperate to establish the hub.

Why optimization models are not decision-making tools

In summary, while models do exist, they are not particularly effective as decision-making tools because of the disconnect between their assumptions and real-world decision-making constraints. Transaction costs, exposure to risks, and the burden of operation, to name a few. The implicit stakeholder evaluation framework also has notable limitations, particularly its tendency to treat EHs as mere stopgap solutions for congestion; it generally avoids the implementation challenges inherent in more technical modeling approaches. To address these gaps, this research proposes a new evaluation framework that assesses Multi-Carrier Energy Hubs based on their structural societal value, considering the broader sociotechnical system, shown in Figure 12. As outlined in Chapter 3, a multi-criteria analysis will be developed that incorporates inputs from both the technical model and the implicit stakeholder evaluation framework. Rather than striving for pure multi-objective optimization, the technical model is designed to reflect real-world constraints and support effective decision-making[2]. This acknowledges the “wicked” nature of the problem, in which the definition of the problem and the perceived solution space are closely intertwined. This proposed evaluation framework strives to balance a holistic perspective with practical applicability, ensuring that the resulting analysis proves useful in real-world decision-making processes.

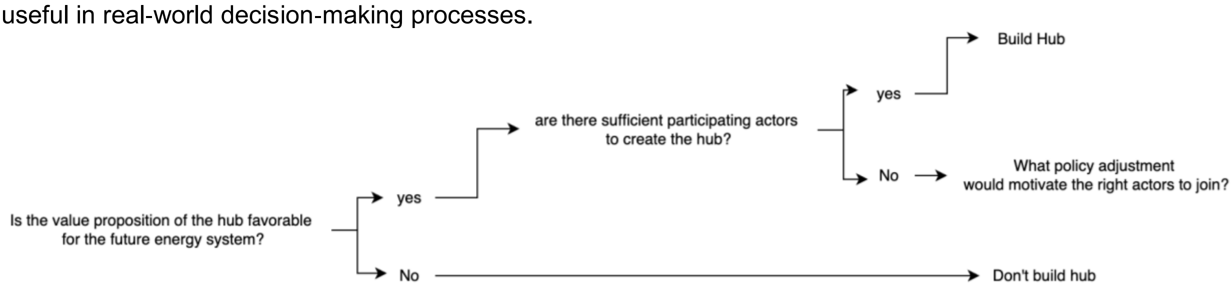

Figure 11, decision tree that merges both stakeholder and technical models as proposed by the research

Integrated decision tree combining stakeholder and technical perspectives. This framework assesses both the system-level value of the hub and the willingness of actors to participate. If participation is lacking, it considers whether policy adjustments could improve feasibility, bridging technical merit with stakeholder engagement.

Table 3 compares the evaluation methods. The table contrasts how each method addresses system performance, stakeholder value, externalities, and implementation feasibility. The proposed evaluation framework aims to address the disadvantages of other methods by combining them.

Table 3, Comparison of evaluation methods

Evaluation Method	Advantage	Disadvantage	Neutral (0)
Implicit Stakeholder Evaluation	• Accounts for indirect costs (e.g., transaction costs) • Facilitates implementation	• Ignores externalities • Depends on all key actors finding it beneficial • Ignores system performance	
Technical Optimization Models	• Focus on system performance • Provide quantitative basis	• Only model what is explicitly included • Ignore stakeholder perceptions • Overlook implementation issues	

[2] Optimization models require clear valuations of flexibility and stakeholder preferences. Yet, assigning monetary values to flexibility is uncertain, and results rely on static assumptions such as future energy use, shifting grid constraints, and evolving market conditions. This makes such outcomes speculative and less relevant for broader societal evaluation.

Proposed Hybrid Evaluation Framework	• Includes system performance and externalities • Considers indirect stakeholder costs • Offers quantitative basis	• Very laborious to conduct	• Some consideration of stakeholder value • Some regard for implementation

3 Methodology

This chapter presents the methods used to answer the MRQ. The research operationalizes structural societal value through a multi criteria analysis (MCA) guided by the Dutch government's MKBA+ framework. This approach ensures a broad welfare perspective by incorporating multiple criteria (economic, environmental, social) beyond purely financial metrics. For the MCA to be performed, criteria must be chosen and then quantified. As the quantifiable results depend on the inputs used, a case study is performed to serve as an example.

3.1 Research Approach

Evaluating MCEHs presents a wicked problem: the definition of the problem, the range of feasible solutions, and the relevant stakeholders all evolve over time. Existing optimization models often capture technical performance but overlook transaction costs and stakeholder acceptance. Conversely, stakeholder-driven approaches ensure participation but typically neglect systemic performance. To bridge this gap, this study adopts a mixed-methods approach combining qualitative and quantitative elements, in line with Swanson and Holton (2005).

The central evaluation method is a Multi-Criteria Analysis (MCA) based on the Dutch MKBA+ (Maatschappelijke Kosten-Baten Analyse Plus) framework. This framework extends the traditional cost-benefit analysis by including broader welfare considerations, economic, environmental, and social, expressed primarily in monetary terms.The research approach is structured around interconnected steps as shown in the research flow diagram in Figure 13.

First, Expert interviews and literature define and validate the MCA criteria, ensuring they reflect real-world decision-making contexts and stakeholder priorities. These interviews also illuminate the inherently political nature of criterion selection, shaped by diverse values and institutional settings. While this introduces a degree of subjectivity, openly addressing it enhances credibility and policy relevance.

Second, a targeted literature review of energy hub models clarifies typical modelling assumptions, decision variables, and existing data gaps. This review delineates technical research boundaries and highlights discrepancies between theoretically optimal hub designs and real-world criteria.

Third, a detailed energy flow simulation model quantifies the effects of various flexibility strategies such as energy storage or curtailment, relative to conventional grid reinforcement. This model translates abstract criteria into performance indicators and enables side-by-side comparison of alternatives under different grid conditions.

Fourth, to validate the approach's applicability, it is applied to a real-world case study of a multi-carrier energy hub. This case study validates the methodology under realistic conditions, allows testing of technological trade-offs, and demonstrates how local factors influence the outcomes.

Fifth, a broader societal literature search is used to operationalize additional externalities related to land use, employment, and emissions, informed by MKBA and "brede welvaart" studies. These factors incorporate value dimensions beyond those captured by the simulation model or highlighted in interviews.

Finally, insights from the expert interviews are used to interpret and contextualize the quantitative findings. This step ensures that the implications are grounded in stakeholder realities, reinforcing the relevance of the results for policy and investment decisions.

Results synthesized from simulations and MCA are presented through comparative outcome tables and cost summaries, clarifying the types and timing of benefits. These comparisons illustrate key trade-offs, emphasizing alternatives where hubs might offer greater societal value despite higher initial costs. Insights from the expert interviews further interpret and contextualize quantitative findings, grounding implications in stakeholder realities and enhancing policy and investment relevance. The integrated approach, balancing qualitative insights and quantitative rigor, ensures comprehensive, stakeholder-aligned evaluation of MCEHs.

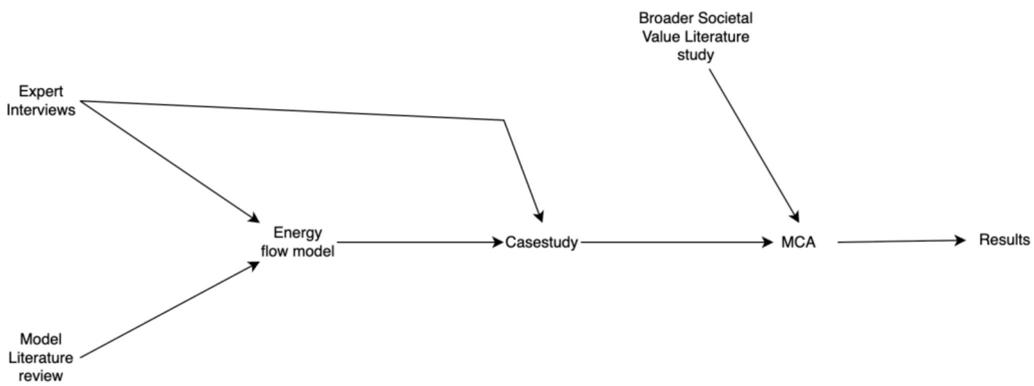

Figure 12, Research flow diagram

This diagram outlines the research process, combining expert interviews, a model literature review, and societal value literature to inform the energy flow model and case study. Together, they feed into a multi-criteria analysis that produces the final results.

3.2 Interview Setup and Execution

The interviews were designed around three core questions,

1. What broader societal considerations influence the preference for grid reinforcement or flexibility alternatives?
2. How do stakeholders value EHs?
3. How do perspectives differ across stakeholder types?

The interview procedure

The expert interviews are structured to understand the perceived challenges and value propositions associated with EHs, as understood by stakeholders involved in or impacted by energy hubs.

A semi-structured interview format was chosen to balance structure with flexibility, allowing for in-depth exploration of stakeholder insights. This approach was particularly suited to the diverse expertise and varying levels of familiarity with EHs among participants.

These findings will provide a foundation for understanding the requirements and characteristics of a model that can effectively evaluate EHs from a broader perspective. Ultimately, the interviews will bridge the gap between individual stakeholder perspectives and the systemic evaluation of EHs, ensuring that the model reflects both business priorities and societal dimensions in energy hub implementation.

Experts with knowledge of three key groups were chosen to ensure a comprehensive understanding of EH dynamics:

- **Grid Operators**: To provide insights into grid constraints, curtailment policies, and potential integration of EHs into grid operations.
- **Grid Users (Industrial and Commercial)**: To understand how EHs influence operational decisions, energy costs, and business expansion opportunities.
- **Public Authorities and Policymakers**: To capture the broader societal and policy considerations driving the development of EHs.

In addition, external experts, such as representatives from EH facilitating companies and researchers, were included to validate findings and provide context. These facilitating companies, such as EQUANS, oversee shared investments in EHs and provide a valuable perspective on the operational limitations and financial mechanisms at play. The interviews also draw on principles of ethnography, focusing on the lived experiences of stakeholders, including their roles, responsibilities, and decision-making processes (Glaser & Strauss, 2017).

The main interview questions were the following:

1. Why are you involved with the energy hub or the process surrounding it?
2. What purpose does the EH serve or need to serve from your perspective?
3. What are the primary drivers and barriers for your participation in an EH?

The interviews also explored:

- Stakeholders' perceptions of flexibility measures, such as curtailment and energy storage.
- The interplay between grid capacity, energy dynamics, and market structures in shaping decisions.
- Stakeholder-specific incentives, priorities, and challenges.

Pre-interview communication included an introductory message with a brief outline of the research questions and scope and the informed consent form requesting permission to record, as included in Appendix B. A meeting link was provided for online interviews.
Each interview was structured into three parts:

1. Introduction, which included reconfirming recording consent, introducing the researcher and study, and discussing the participant's background.
2. The core interview is structured around three guiding questions with room for elaboration.

3. A closing section to summarize responses and clarify remaining questions.

After the interviews were conducted, they were summarized, and their answers to the core research question were assessed, as well as any additional relevant insights. For each interviewee, a unique anonymized function description was created. Post-interview, a transcript summary was shared for participant validation, ensuring accurate representation of viewpoints, allowing them the opportunity to revise their responses, whether by adding, removing, or adjusting their statements. In total, 12 interviews were included in the analysis, and are included in Appendix C.

Validation of interview findings

The aggregated stakeholder perspectives serve to clarify their roles, resources, and ambitions. To ensure validity, interview findings are cross-referenced with insights from gray literature, policy documents, and academic research. Reliability is addressed through peer validation, where anonymized and summarized perspectives are reviewed by other experts. While efforts have been made to mitigate limitations, it is important to acknowledge that certain constraints remain inherent to the methodology. Specifically, interview findings were reviewed with (1) another researcher focused on EHs, (2) a grid area manager with no direct EH involvement to compare value perceptions, and (3) a system strategy expert to align interview and literature findings.

Analysis and thematic processing

A thematic analysis approach was employed to systematically derive insights from the interview data. This method facilitates the identification of recurrent patterns across diverse participant responses, allowing for the structured comparison of stakeholder perspectives. During the initial stage of analysis, emergent themes were recorded in conjunction with the specific viewpoint expressed by each interviewee. This documentation process was conducted on an individual basis to preserve the contextual nuance of each contribution. Subsequently, when a theme recurred across multiple interviews, the varying interpretations were juxtaposed and organized by stakeholder category. This facilitated a comparative analysis across the different groups. For instance, whereas grid operators emphasized risks associated with impacts on higher grid levels, capacity users predominantly highlighted difficulties related to information sharing, an issue also recognized by grid operators, but notably absent from the responses of governmental stakeholders' perspective. Each theme was summarized into a sub-conclusion where stakeholders agree and diverge. These sub-conclusions form the basis of the stakeholder analysis, with extra observations added only when they clarified or exposed unexpected dynamics. Next, the synthesized perspectives were contextualized using both gray and academic literature. This step aimed to assess whether the stakeholder views aligned with documented cases or theoretical frameworks. For example: "Do the stakeholder views align with known examples? Are the formal (gray literature) perspectives different from those encountered in practice?"

Interviews as a research method have inherent limitations

Researcher bias was countered by cross-referencing the research performed by another researcher who conducted similar interview-based research to compare findings and ensure consistency, improving objectivity and reproducibility. Framing effects were limited through open-ended questions, while interpretation bias was reduced by real-time clarification of key terms (e.g., "energy hub," short/long timeframe, desirable outcomes). Sampling bias linked to corporate sponsorship, prevalent grid-operator ties, and many participants' prior EH involvement was managed by aggregating responses into broad categories, ensuring that mention frequency shaped only intra-group weighting.

The sample drew on varied projects, companies, and backgrounds and included one interviewee with no EH experience. Participants were unaware of one another to deter strategic or coordinated answers. These measures substantially reduce, though do not eliminate, residual bias.

Expected Outcomes

The interviews should reveal the stakeholder priorities, barriers, and perceived value in the context of EHs. Specifically, they will answer SRQ1: *What broader societal considerations influence the preference for grid reinforcement or flexibility alternatives?* by providing a nuanced answer to:

1. **Stakeholder Roles and Ambitions**: Clarifying the responsibilities and priorities of key actors in the energy hub ecosystem, including their expectations and concerns.
2. **Drivers and Barriers**: Identifying the motivations behind EH participation and the obstacles that stakeholders face.
3. **Energy Dynamics and Value Perception**: Unveiling how market dynamics, cost structures, and operational flexibility influence decision-making and perceived value.

3.3 A Decision Support Tool: The Energy Flow Model

The simulation model quantifies the system-level impacts of flexibility measures within an MCEH. It is an explanatory decision support tool rather than prescriptive: instead of identifying an optimal set of flexibility measures, it evaluates how a predefined mix of storage, conversion, and curtailment compares to conventional grid reinforcement. Avoiding optimization explicitly recognizes the inherent uncertainties and context-dependent values associated with these measures. For each set of load profiles, asset parameters, and network constraints, it calculates key performance indicators such as peak-load reduction, curtailment hours, state-of-charge trajectories, and indicative costs. These results provide a transparent numerical foundation for the MCA in the next chapter, enabling a structured comparison of alternative hub configurations under different boundary conditions. The method resembles bi-directional soft model linking, as presented by Santos Oliveira et al (2024). The output of one model, here the energy flow model, is linked to the cost model and the implicit stakeholder evaluation, this allows the model to operate independently while benefiting from the other's model's strengths. To clearly frame the operational scope, the next section defines the system boundary and fundamental assumptions that underpin the model structure.

3.3.1 Model Structure & Input Parameters

The simulation replicates energy flows within a clearly defined multi-carrier system boundary: the MV grid connection, gas, and heat sink/source nodes. All internal energy interactions, including stakeholder decisions on flexibility measures, occur within these boundaries. Electricity exchanges are constrained by hourly supply and demand limits, whereas gas and heat are assumed unconstrained. Figure 14 visualizes internal hub energy flows and external interfaces, clearly delineating the model boundary.

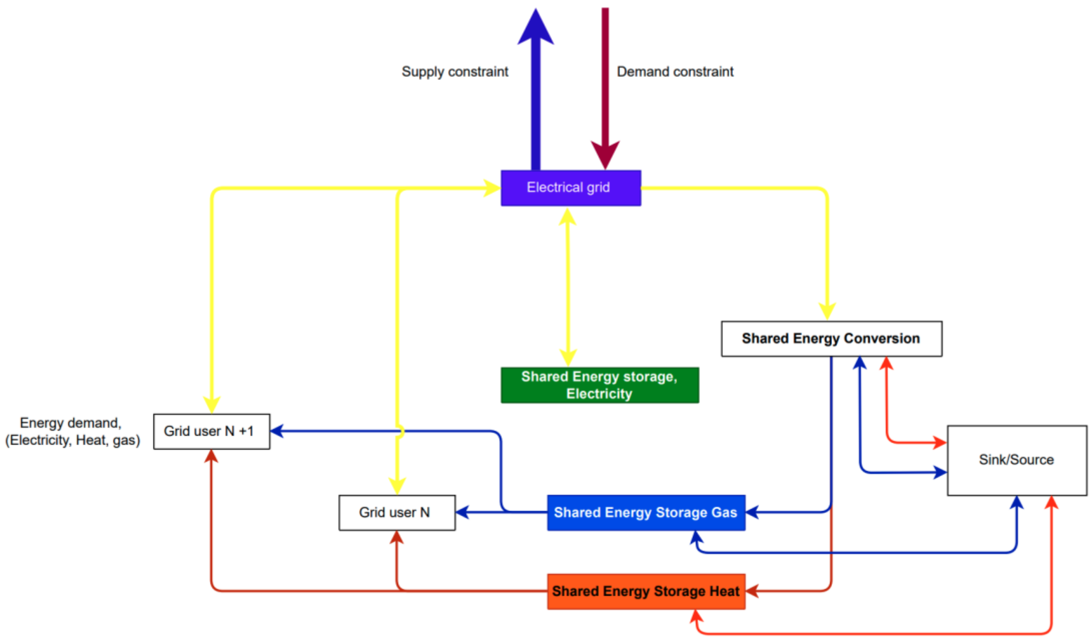

Figure 13, schematic representation of the hub

This diagram visualizes the structure and energy flows within a multi-energy hub. It illustrates interactions between grid users, the electrical grid, shared energy storage (electricity, gas, heat), conversion technologies, and external sinks/sources, while highlighting supply and demand constraints that shape system behavior.

To effectively operationalize this boundary, the model incorporates the following explicit assumptions:

1. The MV ring is assumed to have sufficient internal grid capacity to handle energy exchanges without additional constraints.
2. Heat and gas exchanges are treated as independent variables that do not impose constraints on the electricity grid.
3. Emission costs and external subsidies are excluded from energy costs as societal costs are the sum of all costs, regardless of who pays.
4. The primary bottleneck addressed is the MV ring, necessitating flexibility interventions. No other bottlenecks restrict the transport capacity.
5. The reduction of grid capacity use through curtailment does not result in a shift in capacity use later.
6. The model relies on future energy consumption and price data, which are estimated or based on current data.
7. No dynamic pricing or market effects are considered.

Given these assumptions, it is essential to clarify the entities and interactions explicitly represented in the model.

Defining the Energy Hub's System Boundary and External Interfaces

The simulation models three core entities to represent the interaction between them. Each unit has distinct energy behaviors. These entities, defined at the outset of the simulation, are categorized by their role in the hub:

1. **Grid Users:** Entities consuming or generating energy (factories, solar farms), characterized by hourly load profiles (positive for consumers, negative for producers).
2. **MV Grid:** Facilitates energy transport with predefined hourly capacity constraints. Exceeding these constraints triggers congestion.
3. **Flexibility Assets:** Measures such as demand curtailment, storage (dis)charging, and energy conversion that address congestion and maintain operational limits.

The simulation adheres to three core principles:

1. **Energy Balance:** Ensuring that the sum of energy inputs is equal to the sum of energy outputs across the system.
2. **Constrained by electrical transport capacity:** Flexibility measures adapt energy flows to grid transport limits.
3. **Quantifies Local Flexibility:** Measuring the impact of flexibility on grid congestion, clearly distinguishing between grid constraints and their operational implications.

These principles are operationalized using detailed and structured input parameters, as explained in the subsequent section.

Input Parameters

The simulation model relies on detailed energy profiles to evaluate energy flows and flexibility measures within the multi-energy hub. These inputs form the foundation for understanding how the energy hub operates under grid constraints and flexibility alternatives. The construction and utilization of these profiles are outlined below:

1. **Grid Users:** Detailed load profiles specifying electricity, heat, and gas consumption in timed intervals.
2. **Storage Units:** Parameters including capacity, (kWh), charge/discharge rates (kW), efficiency (%).
3. **Conversion Units:** input/output capacities (kW), conversion efficiencies (%).
4. **Electrical Grid:** A medium-voltage ring with predefined hourly supply and demand capacity limits (kW).

Table in Appendix D, input parameters

3.3.2 Grid Constraints and Equations

In an energy hub, the grid's aggregated load at the congestion point equals the sum of all hub participants' loads and all external non-hub loads. We assume non-hub loads are given, exogenous and will not change due to processes within the hub and are given for each hour. The following equations formalize these balances and the resulting grid capacity limit for the hub. All symbols are defined in kW and at each time step unless noted otherwise.

Grid constraints

Grid constraints define the transport capacity available to the energy hub and ensure the grid remains within its operational limits. The aggregated total load at the grid congestion point combines the load profiles of both energy hub participants (hub users) and external users (non-hub users) and is provided by the grid operator. The non-hub users are taken out of the equation as it is assumed that their load profiles will not change. The equation for an energy balance for a closed system represents this relation.

Equation 1, Aggregated load balance (closed system)

$$E_{\mathrm{agg}} = E_{\mathrm{hub}} + E_{\mathrm{non}}$$

E_{agg} (kW): aggregated total load at the grid congestion point.
E_{hub} (kW): total load of all hub users (participants in the energy hub).
E_{non} (kW): total load of all non-hub users (external loads treated as fixed demand).

This closed-system balance ensures that the total grid load equals the sum of hub and non-hub loads. In practice, E_{non} is treated as a known quantity (given by the grid operator) and does not change in the model. The energy hub thus manages E_{hub} internally. This formulation reflects the idea of an “energy island” where collective supply and demand are balanced by an Energy Management System.

Equation 2, Energy balance closed system rewritten

$$E_{\mathrm{non}} = E_{\mathrm{agg}} - E_{\mathrm{hub}}$$

This is simply Equation 1 solved for E_{non}, it isolates the contribution of external (non-hub) loads by subtracting the hub’s load from the total. The aggregation of load profiles is illustrated in Figure 15, where individual load profiles (colored lines) and their cumulative aggregation (brown line) is plotted over time. For example, the purple line may represent the output of a solar farm, and the red line may represent a small windmill's generation profile. This illustrates how each load contributes to the sum.

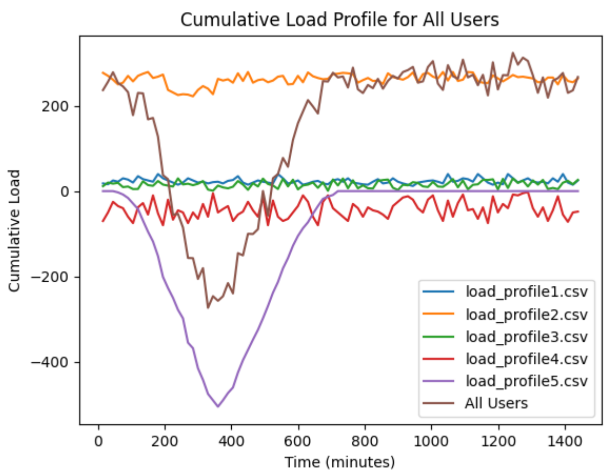

Figure 14, Example of load profile aggregation

The figure shows individual user load profiles (colored lines) and their cumulative sum (brown line) over time. It demonstrates how each profile contributes to the aggregated external (non-hub) energy load, as referenced in Equation 1.

Open-System Transport Capacity

The hub interacts with an open system, where the transport capacity at the interface dictates the possible in or outflow of electricity. The maximum transport capacity of the grid at the congestion point (e.g., 50 kV supply and demand) is retrieved from specification data and is supplied by the grid operator. The transport capacity available to the hub is then derived by subtracting the non-hub users' contribution.

Equation 3, Energy balance open system

$$C_{\text{hub}} = C_{max} - E_{\text{non}}$$

$\mathrm{C_{hub}}$ (kW): available grid capacity (transport capacity) remaining for the hub after accounting for non-hub load.
$\mathrm{C_{max}}$ (kW): available grid capacity (transport capacity) remaining for the hub after accounting for non-hub load.

This constraint applies separately to power imports (supply) and exports (demand) at each hour. It states that the hub's available capacity C_{hub} is the grid's capacity limit minus the fixed non-hub load. The hub can only use the remaining bandwidth of the line. Physically, this enforces that power flows do not exceed the transformers capacity at the MV station. Figure 16 depicts an example of the transport capacity available to the energy hub (blue and yellow dotted lines for suppl of the transformery and demand constraints, respectively). The aggregated load of hub users is shown in green, with red sections indicating instances where the load exceeds the constraints. These visualizations help identify periods of grid congestion and evaluate the effectiveness of flexibility measures in managing energy flows.

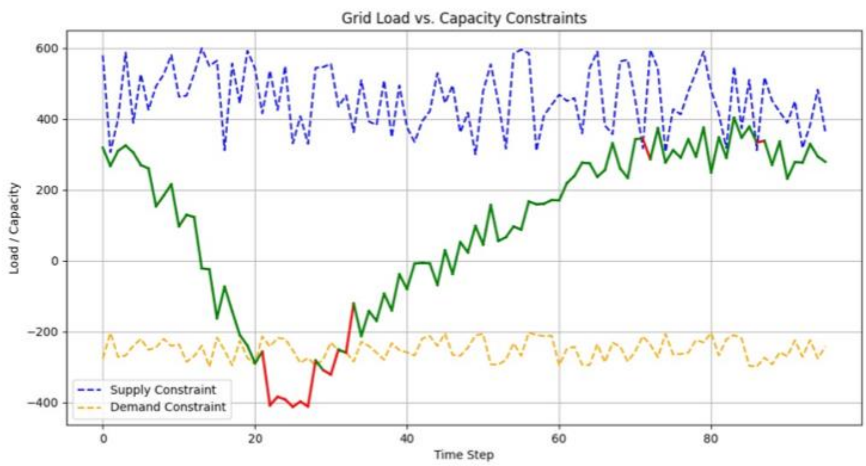

Figure 15, supply, demand constraint example.

This figure illustrates the energy hub's aggregated load (green line) relative to the grid’s available transport capacity. Supply and demand constraints (dotted blue and yellow lines) define the hub’s usable capacity. Red segments mark periods where hub load exceeds these constraints, indicating congestion and the need for flexibility measures.

The model aims to reflect real-world constraints dynamically. While the Noordring grid constraint appears static (e.g., ±55 MW in Figure 17), the actual space available for hub use dynamically fluctuates with non-hub users’ load. Thus, grid constraints at the hub level vary hourly, accurately reflecting operational limits and informing necessary flexibility measures.

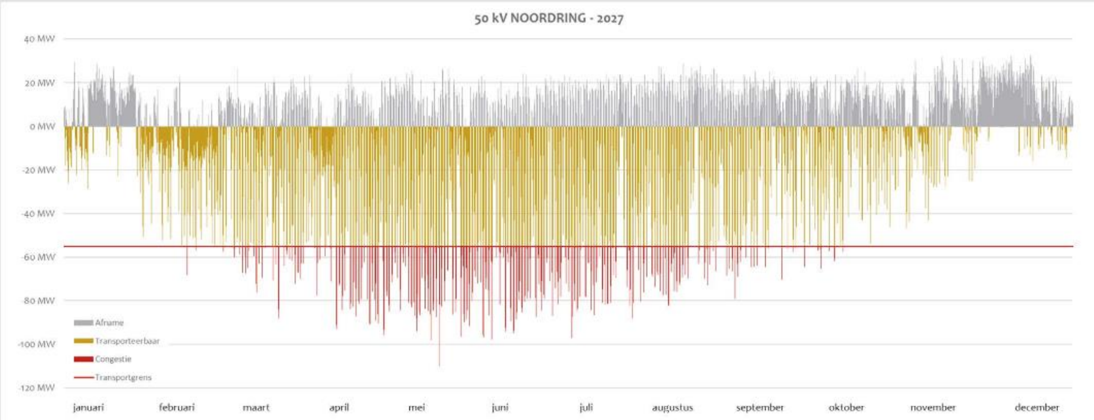

Figure 16, Noordring from investeringsplan 2024 Stedin

This graph illustrates the hourly fluctuations in grid load on the 50 kV Noordring expected in 2027. While the formal transport capacity appears fixed (±55 MW), the figure highlights how non-hub user behavior causes dynamic variation in actual available capacity.

3.3.3 Solver Logic: the dispatch order of flex measures

Sequential steps dictate what and when flexibility is applied. Flexibility is primarily used to maintain grid stability by ensuring that energy flows remain within the capacity limits of the medium-voltage MV grid. When constraints are exceeded, flexibility measures, such as storage, energy conversion, and curtailment, to mitigate congestion and restore balance.

1. **Grid Capacity Check**

The total energy load from all grid users is aggregated and compared against the MV grid's supply and demand constraints as specified in the grid's load profile. If the total load is within the grid's capacity, opportunities to utilize any surplus capacity are assessed. Conversely, if the aggregated load exceeds grid limits due to either high demand or excessive generation, flexibility measures are initiated.

2. **Application of Flexibility Measures**

   If the aggregated load surpasses the grid capacity, the logic applies flexibility measures in the following prioritized order:

   a. **Storage Utilization:** Available storage units are evaluated first. Excess energy is directed into storage systems, and energy deficits are compensated by discharging these units. Storage operations adhere strictly to predefined maximum charge and discharge rates and efficiency limits.

b. **Energy Conversion:** If storage measures alone are insufficient, energy conversion units are utilized next. Excess electricity may be converted into heat or gas for storage, while stored heat or gas can similarly be converted back into electricity when necessary. Conversion operations respect the efficiency and capacity limits defined for each unit.

c. **Curtailment:** If both storage and conversion measures prove inadequate, curtailment is implemented as a last resort. Curtailment involves reducing energy production or consumption to comply with grid constraints, prioritizing the reduction based on the lowest curtailment costs to minimize economic impacts

3. **Surplus Capacity Utilization**
When grid operations remain within capacity limits, available flexibility measures may proactively be utilized. This involves charging storage units or converting energy to prepare for anticipated periods of higher demand or increased energy costs. The management of storage follows a predefined State of Charge (SOC) strategy aimed at optimizing economic outcomes, operational flexibility, or both.

3.4 Multi-Criteria Analysis

To evaluate the societal value of energy hubs, this research applies a Multi-Criteria Analysis (MCA) aligned with the Dutch MKBA+ framework. This method allows system performance, firm-level economics, and broader societal effects to be compared within a unified decision framework (Planbureau voor de Leefomgeving [PBL] & Centraal Planbureau [CPB], 2022). Where possible, impacts are monetized in euros to avoid subjective weighting and enable direct comparison.

The MCA criteria were derived through three steps:

1. **Policy relevance**: A review of MKBA and "brede welvaart" guidelines identified impact categories used in Dutch public investment appraisal.
2. **Stakeholder validation**: Semi-structured interviews confirmed which of these categories mattered in practice and added items such as curtailment risk and transaction costs.
3. **Operational feasibility**: Criteria were included only if they could be quantified, either by the simulation model or via standard unit values from the literature.

This process resulted in a balanced set of indicators, capturing both public and private value.

Two information streams were combined to construct the effect inventory required for an MKBA. First, interviewees explained which impacts they weigh when deciding whether to join an energy hub; they described how they perceive value. Second, the literature on societal consequences of energy hubs was reviewed to capture additional effects that might matter but are not always visible to individual stakeholders. Finally, an operational check was performed, where each candidate criterion was kept only if it could be quantified with available data: either *directly* by the energy-flow model (e.g., peak-load reduction) or *indirectly* by applying documented unit values from the literature. The result is a balanced indicator set that captures both private and public value and therefore allows an evidence-based comparison between energy hubs and conventional grid reinforcement.

3.4.1 Linking the Model and the MCA

The simulation model, interviews and MCA are tightly integrated. The interviews conducted at the start of the project determined both the boundaries of the simulation model and the angle of the evaluation, so the model ends up performing two tasks at once. First, it mirrors the design space: Parameters that future hub participants can influence, such as conversion size, battery capacity, or demand-response settings, are explicitly represented. Second, it acts as the calculation engine for the MCA, producing most of the numerical indicators that subsequently feed the assessment. The model thus not only reflects the technical options stakeholders can influence (e.g. battery size, conversion assets), but also produces most of the numerical indicators used in the MCA.

MCA criteria fall into three categories:

- **Direct**: Output is already in the required unit (e.g. curtailment hours).
- **Indirect**: Requires post-processing (e.g. costs due to lack of access).
- **Deduced**: Inferred from design choices (e.g. land use implications of certain technologies).

Several factors are deliberately omitted because they are already governed legal standards, detailed in Appendix B, interview 11. CO_2 and other regulated emissions, along with biodiversity, air, soil, and water-quality impacts, fall into this category: existing legal minima ensure that any feasible design will satisfy them, so they do not differentiate alternatives. Subsidies are another exclusion. They are policy levers intended to reconcile private and societal business cases; while they affect who pays, they leave total societal value unchanged and therefore do not belong inside the MCA itself.
On the other hand, several factors are indispensable. Material scarcity can constrain the viability of certain technologies. Land and underground space requirements remain critical, not only for installing batteries or electrolyzers but also for accommodating the upstream supply chain these assets depend on. Finally, the analysis must keep track of systemic interactions between low- and high-voltage networks.

3.4.2 Case Study: Tholen Industrial Estate

The Tholen industrial estate was selected as the case study to test and illustrate the methodology under realistic conditions. Several factors made Tholen particularly suitable: it has a clearly defined congestion point at the medium-voltage station; an operational energy hub already exists; detailed load profile data was made available by the grid operator (Stedin, 2024); and previous research and stakeholder knowledge are well documented.[3]
Using a real-world case enables the method to be applied to a known system with realistic constraints. The case allows for the testing of alternatives to explore trade-offs between flexibility measures and conventional grid reinforcement. By drawing on an existing setting, the model can be

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[3] *Publicly available reports, earlier academic and consultancy studies with the REC Tholen stakeholders, expert interviews*
(Stedin, 2024; REC Tholen, n.d.; Niers, 2024; Aalders, 2024; van Stokkum et al., 2022).

calibrated with greater credibility, and its modular design ensures that the approach remains transferable to other locations.
Although no direct interviews were conducted with firms active in REC Tholen for this study, stakeholder objectives were reconstructed from publicly available reports, consultancy documents, and interviews with sector experts. These include prior studies by Odile Niers, who focused specifically on REC Tholen participants. Together, these sources provide a reasonable proxy for the interests and constraints of local stakeholders, allowing for a first-order exploration of systemic trade-offs.
These proxy objectives are embedded into the energy flow simulation model, which evaluates a set of flexibility alternatives against the baseline of grid reinforcement. This comparison generates the quantitative inputs for the Multi-Criteria Analysis, which assesses each configuration in terms of societal value.

The Tholen case thus serves two purposes: it grounds the model in a realistic operational context and demonstrates how the methodology can be applied in practice. It also illustrates how flexibility options can be tailored to site-specific constraints and stakeholder needs. The full case description, including data sources, assumptions, and configuration details, is provided in Chapter 6.

3.5 Why are These Methods Fit to Answer the MRQ

The mixed-method design reflects the complexity of the research topic. To address the MRQ, technical modeling and stakeholder perspectives are combined.

Research Objectives 1 and 2, shifting the evaluation lens and broadening the scope, are addressed through interviews.
The expert interviews play a key role in shaping the analysis. They clarify how real-world actors perceive costs, risks, and responsibilities, and reveal what factors they use in decision-making. This input is essential to ensure that both the model and the evaluation criteria reflect practical realities and not just theoretical assumptions. The interviews expose transaction costs, regulatory constraints, and decision parameters that would otherwise be difficult to quantify.

Objective 3, clarifying interaction effects, is met through the simulation model and case study.
The technical model complements this by simulating how energy hubs operate under different conditions. It provides insight into the interaction of technologies like storage and curtailment, helping to understand their potential to relieve congestion or reduce costs. Rather than treating these effects in isolation, the model evaluates them as part of a larger system. Applying the model to a real industrial estate ensures that the simulations are grounded in realistic circumstances and helps validate the model’s behavior.

Together, these qualitative and quantitative methods provide a structured yet flexible approach to evaluating the value of energy hubs in a transparent, context-sensitive, and practice-oriented way.
Finally, the findings are interpreted using insights from the stakeholder interviews, which helps relate the technical results back to the institutional and political context. This step ensures that conclusions are not only analytically sound but also relevant for decision-makers.

Chapter 4 presents the interview results that shape both model scope and MCA criteria; Chapter 5 reports simulation outcomes and validates them on the Tholen estate; Chapter 6 combines these with societal factors in the MCA to answer SQ2 and the MRQ, with Chapter 7 discussing robustness and policy implication.

4 Interview Results

Chapter 4 presents the results from interviews conducted to inform the evaluation criteria for multi-carrier energy hubs. First, the stakeholder roles and perspectives are presented to function as the context in which the results are placed. The interviews also serve to substantiate the inclusion of model parameters. Then the key misalignments, followed by the value perception and motives is presented. These are then translated into MCA criteria which are quantified model in chapter 6.

4.1 Stakeholder Perspectives

This section builds upon 2.4, where the stakeholders and their institutional context are introduced. The interaction between stakeholders and hubs is described, based on how hubs are perceived and interacted with in practice. Hubs depend on the cooperation of stakeholders, making them inherently multi-actor systems. However, their definition and purpose vary greatly depending on the stakeholder's perspective. ***It is crucial to note that there is no single, universally accepted definition of what an EH is. Instead, stakeholders view EHs through their own lenses, applying them as solutions to distinct problems and evaluating them within unique frameworks***. This multiplicity of interpretations shapes how EHs are implemented and highlights the complexity of aligning stakeholder objectives. Understanding these dynamics is key to addressing why EHs often face implementation challenges and how their value is understood.

One interviewee acknowledged, "Each partner has its own definition of an 'energy hub' and distinct goals for it, so we often aren't even talking about the same thing, everyone has different expectations." Such divergent interpretations mean that what one actor considers the core purpose or benefit of the hub might barely register for another.

4.1.1 Grid Users

Grid users, primarily companies and particularly SMEs, are often unaware of EHs until they are directly affected by grid congestion. Most do not actively seek out or plan for participation in EHs unless a capacity crisis compels them to do so. A growth surge, an electrification mandate, or a price shock can cause an immediate jump in transport demand, and any capacity shortfall can stall expansion, leading them to explore alternatives to grid transport. As one expert noted, "Companies will only begin seeking EH solutions if they are faced with urgent issues". This illustrates that engagement is typically reactive and driven by acute necessity rather than strategic ambition.

When grid users start exploring hubs, they often have a limited understanding of what participation and ownership in an EH entails. Many envision ready-made solutions, underestimating the coordination and ramp-up time required for successful implementation. As one consultant observed, companies tend to frame EHs as crisis responses or revenue models, whereas operators approach them from a long-term, systemic perspective. This mismatch in expectations frequently leads to friction and delays.

Smaller and mid-sized enterprises are focused on their core business activities and often lack the capacity or knowledge to explore EH opportunities[4], unless such engagement becomes unavoidable. For these users, EHs are seen primarily as pragmatic instruments to maintain operational continuity or to expand electricity usage in the face of grid congestion or delays in grid reinforcement.

While secondary motivations such as sustainability, cost optimization, or the valorization of flexibility are acknowledged, they typically become relevant only after security of supply has been addressed. Crucially, many firms do not take responsibility for broader societal outcomes, and their use of EHs as emergency solutions tends to overlook the systemic performance of the energy system.

This stands in contrast to grid operators and public authorities, who are generally more familiar with the concept of EHs and recognize their role within the future decentralized and flexible energy system. These differing points of departure reflect a fundamental asymmetry in awareness and evaluative frameworks. For businesses, the value of an EH lies primarily in immediate and tangible benefits. Their willingness to participate is highly dependent on the clarity and positivity of the business case.

4.1.2 Operators

Grid operators, function as both gatekeepers and enablers in the development of EHs. Their core mandate is to ensure the affordability, reliability, and security of energy supply, which shapes how they engage with other stakeholders.

There is a nuanced divergence in how grid operators perceive EHs. Many still view them as temporary instruments for alleviating congestion.

> *For example, a senior manager from Stedin referred to EHs as "a temporary solution to better utilize the limited grid capacity." Yet, others within the sector acknowledge a broader role: "EHs are currently mainly positioned as solutions for acute congestion problems, but they also have a broader role in a future energy system."*

This divergence often reflects the institutional and regional context of the operators themselves. DSOs embedded in more proactive environments or facing more acute grid pressure (e.g., Enexis, Alliander) tend to integrate EHs into long-term strategic planning, while those in less pressured regions remain reactive. This reflects a broader governance tension between mandated responsibilities and the discretion to interpret and operationalize them. Nevertheless, a more structural and strategic interpretation of EHs is beginning to gain traction. Institutional economics helps explain this shift. As regulated actors operating under the unbundling directive, DSOs are legally constrained from owning or operating generation and storage assets. This limitation compels them to rely on external actors for flexibility, reinforcing a cautious and risk-averse culture. As one innovation advisor explained, “we lobby for user-driven curtailment because we can’t own storage or

[4] Big industrial firms on the other hand join EH projects with a long view of 5 years or more, seeking to optimize cost, but these hubs are usually not aimed at congestion.

generation, but we still need visibility of what the hub is doing as it impacts the rest of the grid.” Such statements reflect a system logic oriented toward safeguarding reliability without assuming direct operational control.

Operators evaluate EHs through an energy system lens, assessing their capacity to manage peak loads, defer reinforcements, and maintain technical stability. As one strategist summarized: “First a quick MV-ring feasibility scan, then a TSO check for upstream impact, before we give a firm capacity answer.” From their perspective, EHs help manage congestion without resorting to costly grid reinforcements.

Despite and due to their public ownership and mandate to safeguard societal value, DSOs often operate within risk-averse institutional cultures (see Chapter 2). They are not market participants and thus lack incentives to take on entrepreneurial risks. Their engagement is motivated by both operational necessity and legal obligations, such as offering connection options. Tools like non-firm access contracts are increasingly used to navigate infrastructure bottlenecks. Strategic integration varies: some DSOs embed EHs into long-term planning, others remain reactive.

Coordination remains essential, even where hubs operate "behind the meter", where they would theoretically not be needed, to ensure system-level benefits. All congestion is undesirable, but it doesn't always present a critical operational issue in the daily practice of the operator. Congestion may just as easily be triggered by a large low-voltage feeder in the next village as by the hub’s internal load (PVB Nederland, 2024; Stichting Stimular, n.d.). The capacity of a shared MV-connection is, in this context, a dynamic constraint; its limit is defined not only by the hub’s internal load but by surrounding grid activity.

The interaction between DSOs and the TSO further complicates matters. Congestion on the high-voltage grid can cascade downwards, while local flexibility might unintentionally worsen conditions elsewhere. As one advisor cautioned, “A challenge is the coordination with TenneT. At certain times, it can happen that a local peak load by an Energy Hub coincides with a peak elsewhere in the higher grid.”

“For the grid operator, the primary task of an EH is to enable transport capacity within a set limit, especially in congestion areas. In addition, it offers entrepreneurs a perspective for action: insight into what is possible and agreements that provide clarity and certainty” (Consultant strategic development).

Ultimately, grid operators seek to maximize public value through regulated service delivery. Their involvement in EHs is shaped by their public mandate to provide affordable, reliable transport capacity and by the broader institutional environment in which they operate.

4.1.3 Government

In contrast to both users and grid operators, governmental entities approach energy hubs from a long-term, strategic perspective, unless they have a specific project in mind[5]. Their interest in EHs goes beyond operational feasibility or immediate cost savings; instead, they see EHs as instruments to support overarching societal goals, including climate action, social equity, regional development, and innovation.

This strategic orientation means that governments may engage with EHs even in the absence of acute congestion. For example, municipalities may initiate or support hub development to align with spatial planning ambitions, promote sustainability, or stimulate local economic resilience.

Despite this proactive stance, EHs' actual contribution to public goals depends heavily on their design and implementation. Their impact on emission reduction, energy equity, or regional vitality often remains abstract. The tension between policy ambition and practical realization is reflected in the grey literature, where EHs are included in their vision of the future yet not concretized.

To move beyond vision and address this implementation gap, national government agencies like the Rijksdienst voor Ondernemend Nederland (RVO) have begun offering targeted support. This includes funding, coordination, and facilitation to help EHs materialize in regions where private initiatives alone are insufficient (RVO, n.d.-a; RVO, n.d.-b). These interventions underscore the governmental belief that EHs, if well-designed and context-sensitive, can reconcile private incentives with long-term public value. financial support to help EHs emerge in regions affected by congestion or where business cases are otherwise too weak to mobilize private initiative alone.

However, governmental engagement is not uniform across the country. While some regions, such as the port of Rotterdam, have embedded EHs into multi-year infrastructure agendas, using them as instruments to anticipate future grid bottlenecks and stimulate resilience, others remain largely passive. The extent to which EHs move beyond the drawing board depends on policy coherence, regional ambition, and the capacity to translate strategic visions into concrete, actionable projects.

4.2 Stakeholder Value Perception

This section shifts from the perception of hubs in 4.1, to how and what value hubs provide. It explains how stakeholder incentives influence EH engagement how the model quantifies these choices. These insights directly influence the quantifiable parameters used in the simulation model and multi-criteria analysis.

Stakeholders attribute value to EHs based on distinct criteria:

- **Grid Users** emphasize immediate and tangible benefits, energy access, supply reliability, and cost-efficiency. Companies facing constraints push for quick timelines: they often “Want a quick solution, within several years or sooner” to address their capacity problems. The EH must provide short-term relief. Businesses, especially SMEs, view EHs as essential for maintaining continuous operations and potentially reducing energy-related expenses. For companies, environmental benefits (CO_2 reduction, sustainability) are a welcome secondary motive once energy supply and cost criteria are met.

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[5] *The Port of Rotterdam, WarmtelinQ, and Energie in balans Flevoland* are all projects where the province, municipality or national government actively participate because they have vested interests as shareholders or otherwise.

- **Grid Operators** primarily perceive EHs as instruments for the better utilization of grid capacity and deferring some of the grid reinforcement. Their planning horizons typically span multiple decades, aligning with the extended capital recovery periods mandated by the Dutch regulatory authority (ACM). Nevertheless, in contexts of acute congestion, EHs are often deployed as reactive solutions to immediate operational challenges. In such cases, DSOs prioritize addressing current grid issues over long-term strategic integration. Despite this, DSOs recognize the strategic value of EHs in mitigating congestion, thereby potentially reducing the need for frequent and large-scale grid reinforcements. Moreover, EHs are valued for their capacity to introduce flexibility into the energy system, contributing to enhanced grid stability and responsiveness.

- **Government Entities** attribute strategic and long-term value to EHs, viewing them as catalysts for regional economic growth and sustainability. Governments value EHs for their potential to accelerate renewable energy integration, enhance local resilience, and support broader policy objectives, such as climate action and economic diversification.

Economic and Financial Considerations

Financial clarity and viability remain essential for stakeholder engagement, especially among businesses:

- **Grid users** require a clear and immediate financial incentive to participate. Without demonstrable short-term cost savings or revenue opportunities, businesses show reluctance to engage with EHs. Regulatory complexity and financial uncertainty frequently pose significant barriers. The source notes that "Many companies are uncertain about investments in EHs due to the lack of solid business models and clear financial benefits." In practice, if the benefits are unclear or too long-term, companies hesitate to join. This sentiment was echoed by multiple interviewees: the complexity of current regulations and lack of proven examples make firms wary.
- **Grid operators** recognize the necessity of economic incentives to engage businesses and actively advocate for models that align stakeholders' financial interests, such as cost-sharing mechanisms or the introduction of alternative transport contracts.

Individual versus Collective Value Dynamics

Interviews highlighted an essential tension between individual incentives and collective benefits critical to EH success:

EHs inherently rely on cooperative behavior: sharing infrastructure, investment, and operational data. However, individual stakeholders, particularly businesses without immediate capacity constraints, often prioritize their interests, weakening the potential collective benefits. Several interviewees flagged that companies with sufficient grid capacity or less to gain often opt out, undermining collective solutions. One consultant described this as a fundamental problem: "Companies often think from their own profit perspective, while the success of an Energy Hub depends on collaboration," noting cases where firms with no capacity issues “withdraw,” which makes a collective hub much harder to realize. The participation of these parties is essential for the contractual hubs’ [6]success.

To mitigate this tension, grid operators and government facilitators stress the need for transparent governance structures, equitable benefit-sharing arrangements, and dedicated coordination roles (such as independent orchestrators) to align individual incentives with collective goals effect. Thus, a key to motivating grid users is demonstrating tangible economic value. Grid operators also acknowledge this; they try to present EHs as financially win-win (e.g., sharing the savings from avoided grid fees), and some propose mechanisms like socialized costs or new market roles (e.g. Congestion Service Providers) to improve the business case for all parties.

Table 4 summarizes and compares the stakeholder value perceptions, motives, barriers, and general perspective.

Table 4, Comparative Stakeholder Perspectives and Motives

THEME	GRID USERS	GRID OPERATORS	GOVERNMENT ENTITIES
GENERAL PERSPECTIVE	*Problem-driven:* Tend to view EHs as a means to fix their own capacity issues when they arise. Often not aware of or interested in the EH concept until facing grid constraints.	*System-driven:* View EHs as a tool to manage congestion and optimize the grid. Emphasize technical coordination; currently often treat EHs as pilot or interim solutions (with potential for future scaling).	*Policy-driven:* See EHs as an innovative instrument to prevent local congestion and enable regional energy goals. Focus on collaboration between companies and communities to maximize local energy use.
AMBITION & INITIATIVE	*Reactive:* Little proactive ambition – companies rarely initiate EH projects unless forced by need. Smaller firms especially focus on core business and join an EH only if it’s necessary to obtain power. Larger firms may show more strategic interest, but this is the exception.	*Mixed:* Some DSOs (and individuals within them) are proactive, integrating EHs into innovation strategies and pilot programs. Others remain reactive, participating in EHs primarily to solve acute network problems or when external parties propose them.	*Mixed:* A few municipalities/provinces act as EH champions (proactively including hubs in plans for economic development and sustainability), while others are hands-off until a problem emerges. Ambition can depend on local policy agendas and leadership.
TIMELINE OUTLOOK	*Short-term urgency:* When affected by congestion, demand quick solutions (want	*Immediate action with cautious scaling:* Emphasize starting pilots now to address	*Strategic planning horizon:* Often incorporate EH concepts into multi-year infrastructure and climate

[6] A contractual hub has no storage or conversion assets and relies on a (group) contracts such as the Groeptransportovereenkomst (GTO), collectief capaciteitsbeperkend contract (C-CBC), or Non-firm ATO.

	relief within months to a few years). Otherwise, EH planning is not on their radar. Long-term energy planning is uncommon except for some large corporations looking 5+ years ahead for sustainability goals.	current issues and learn by doing. Urgency is high to implement near-term measures. Simultaneously, forward-looking DSOs are considering how EHs fit into long-term grid planning (e.g. in the next decade), though this strategic horizon is still emerging.	plans (e.g. 2030 goals), seeing them as part of the medium-to-long term solution set. However, they also expect short-term results to alleviate bottlenecks and may push for accelerated implementation in the near term.
VALUE PERCEPTION	*Operational continuity and cost:* Primary value is ensuring reliable power supply so operations can continue and expansion isn't halted by grid limits. Also value any cost savings (through shared infrastructure or energy trading) an EH can provide. Environmental benefits are appreciated but secondary – they become a focus only after reliability and cost needs are satisfied.	*Grid efficiency and risk mitigation:* Value EHs for using network capacity more efficiently, reducing the need for expensive grid reinforcements. Key motives include avoiding overloads, deferring capital investments, and gaining flexibility (through demand response or storage) to manage the system more smoothly. Support of the energy transition is a linked benefit.	*Economic development and sustainability:* Value EHs as a means to enable local economic growth (new businesses or housing can get power without waiting for big grid upgrades) and to meet policy targets for renewable energy and CO_2 reduction. EHs are seen as creating local resilience and autonomy in energy, which aligns with broader societal goals.
KEY MOTIVE BARRIERS	*Requires a clear business case:* If benefits (cost or capacity) are not concrete, companies lose interest. Many are deterred by uncertain return on investment and complex regulations. They also worry	*Institutional constraints:* Regulatory and organizational hurdles (e.g. rules not designed for collective solutions) can dampen DSO enthusiasm. Limited internal resources and risk-aversion within utilities	*Coordination and priority:* Government support varies – some lack awareness or urgency regarding EHs. When not prioritized, there may be no framework or facilitation for hubs. Additionally, aligning EH projects with existing regulations and securing funding can be challenging

	about sharing sensitive data or depending on others, which can reduce willingness to join.	slow proactive EH investment. They need to see that EHs truly help the system long-term to fully commit.	without higher-level policy support.

4.3 Misalignments

4.3.1 Misalignment 1, Different Perspectives

The first misalignment concerns framing and interpretation. Stakeholders fundamentally differ in what they believe energy hubs (EHs) are for and, consequently, how they evaluate their value.
Companies, especially small and medium-sized enterprises (SMEs), typically focus on their core business activities and see hubs as a way to alleviate acute operational challenges when confronted with limited grid capacity.
Grid operators regard EHs as tools to offer perspective to companies with capacity problems and for managing or preventing congestion, without immediately resorting to costly and time-intensive grid reinforcements. Meanwhile, municipalities and provinces, sometimes acting as mediators or initiators, tend to view EHs as instruments for economic development, sustainability objectives, and the prevention of congestion before it becomes a crisis.

One interviewee noted that the mismatch in vision can lead to friction, as "municipalities see energy hubs as a local tool, companies as a temporary solution or revenue model, while the grid operator looks at the larger system and long-term benefits."

These contrasting perspectives lead to confusion. As another respondent put it, "Each partner has its own definition of an energy hub and distinct goals for it, so we often aren't even talking about the same thing." Misunderstandings arise not just from competing interests but also from incompatible visions of what EHs are meant to achieve and how they should be realized.

4.3.2 Misalignment 2, Varying Ambitions

Stakeholders also diverge on what value EHs should deliver and when to act.
Grid users typically become engaged only once congestion poses an immediate threat to operations. At that point, they may seek flex assets, shared-capacity contracts or shift production schedules, provided the business case is viable. Grid operators, constrained by limited staff and long build times, value EHs for the near-term flexibility they provide and now offer group arrangements such as non-firm ATO contracts to manage capacity. Municipalities and provinces, by contrast, may advocate EHs well before bottlenecks arise if it aligns with local political goals or broader societal objectives.

4.3.3 Misalignment 3, Different Timelines

Finally, the temporal dimension poses a significant misalignment. While all stakeholders recognize the urgency of addressing grid congestion, their planning horizons and evaluation timeframes differ sharply.

Grid users, particularly SME facing congestion, want the hub to provide rapid relief and have a shorter investment timeframe and evaluate it as such. Grid operators take a long-term view. Their investments follow decade-scale plans, aligned with tariff regulations and capital recovery schedules set by the Dutch regulator (ACM). As one innovation advisor at a DSO remarked:
“Our investment horizon is 40 years; tariff approval alone can take two. Industry wants relief next quarter.
Companies, on the other hand, operate on much shorter cycles. A sudden growth surge, electrification mandate, or energy price spike can immediately drive-up transport demand. Capacity shortages can quickly stall business expansion. Municipalities and provinces have a long term perspective.

In theory, EHs offer faster relief than traditional reinforcements. Yet their design, negotiation, and implementation involve delays, transaction costs, and expertise. This temporal mismatch separates the theoretical benefits of EHs from their practical feasibility.

4.4 From Interviews to Model Logic

The simulation model, presented in Chapter 5, draws directly on the insights obtained through the stakeholder interviews. Table 5 presents the link between the misalignments and the model. Based on the findings, the following parameters must be included:

User load profile integration.
Transport capacity requirements fluctuate in time, driven by the load profiles of individual users. These profiles directly influence when congestion arises and determine the effectiveness of flexibility measures. The model incorporates real-world load profiles to capture this dynamic behavior and to simulate the timing, frequency, and magnitude of capacity violations. This enables a detailed, time-resolved assessment of flexibility needs.

Time-varying grid capacity constraints.
Interviewees emphasized that MV-level congestion is assessed through local feasibility scans, often in coordination with the TSO. Congestion may originate from factors external to the hub, such as adjacent low-voltage feeders. To reflect this, the model implements a time-varying transport capacity at the MV constraint, accounting for fluctuating non-hub demand. This approach aligns with operator concerns that capacity should be treated as a dynamic variable, not a fixed threshold.

User-side flexibility and curtailment.
Due to regulatory restrictions, grid operators cannot own or operate storage assets and instead promote user-driven flexibility. The model reflects this by assigning each grid user a curtailment capability and corresponding cost. This accommodates the observed diversity among firms: some can adjust their demand flexibly in response to price signals, while others face higher opportunity costs or operational inflexibility.

Business case logic.
Curtailment becomes attractive when the compensation for reducing demand exceeds the cost of production downtime. Additionally, users with storage assets can shift their consumption, charging when prices are low and discharging during peak prices. These mechanisms enable firms to optimize their procurement strategy, reduce energy expenditures, and contribute to lowering system-wide costs.

Table 5, Link between misalignments, the model and MCA

MISALIGNMENT	CORE ISSUE	IMPLICATION FOR MODEL	IMPLICATION FOR MCA
1. PERSPECTIVES	EHs mean different things	Needs flexible inputs	MCA needs multi-perspective criteria weights
2. AMBITIONS	Differing motivations	Include curtailment costs & constraints	Highlight business case heterogeneity
3. TIMELINES	Differing urgency/planning	Model dynamic capacity vs. demand over time	MCA must include feasibility and timing

4.5 The Translation of Interview Results into MCA Criteria

As outlined in Chapter 3, semi-structured expert interviews were used to identify and validate the criteria relevant for the MCA. An overview is presented in Table 6. These interviews helped confirm which value dimensions are considered significant in practice and introduced additional decision-relevant aspects such as curtailment risk and transaction costs. Following the methodology prescribed by the MKBA+ framework, values were first inventoried based on expert input and literature, including sources from Eigen and related Dutch policy evaluations. The resulting value themes are presented in full in Table 1. Each value was subsequently assessed qualitatively from the perspective of key stakeholder groups. Scores range from 1 (minor relevance or “nice to have”) to 3 (critical or “main motive”). The individual values were then grouped into nine overarching categories, which form the structure of the MCA.

1. Grid-Constraint Compliance
This criterion serves as a binary selection condition that determines whether a given configuration is technically feasible. If a configuration violates grid constraints, it is excluded from further analysis. Compliance is assessed as a basic “yes” or “no”: configurations that exceed grid limits are deemed non-viable.
2. Supply Reliability / Business Continuity
This criterion captures the extent to which grid users retain uninterrupted access to energy. It is measured as the number of hours per year during which access is curtailed. The associated societal cost is calculated by multiplying the curtailed energy (in kWh) by the unit societal cost of congestion, based on Ecorys estimates (2024). This results in a yearly monetized impact reflecting reliability losses.
3. Congestion Cost / Lack of Access to Transport Capacity
This indicator reflects the cost of being unable to access the required grid transport capacity. It is

expressed as a yearly cost that persists until the congestion is structurally resolved. For example, if a hub solution is deployed after two years, costs are incurred in the first two years only. If grid reinforcement is scheduled after eight years, the cost recurs annually over that period. These costs are based on the amount of congestion if no additional measures are taken, multiplied by the Ecorys estimate.

4. System Impact

This is a qualitative indicator that captures broader systemic effects, such as innovation spillovers, market structure influence, or long-term energy system transitions, that cannot be reliably quantified within the current modeling scope. As such, it is acknowledged and will only be qualitatively treated in the analysis.

5. Net Annualized System Cost

This refers to the total annualized capital and operational expenditures of hub components. These costs are expressed in net present value terms, discounted at 3% over a 15-year period, and include storage, conversion, and control infrastructure or the alternative grid reinforcement.

6. Total Energy Cost

This category reflects the yearly operating cost for energy consumption, calculated as the product of the energy quantity and the applicable energy price. It provides a financial perspective on recurring energy expenditures under each configuration.

7. Resource Footprint

This indicator captures the environmental impact of raw material use associated with hub technologies. It is assessed qualitatively based on the European critical raw materials guidelines, highlighting issues such as resource scarcity and dependency.

8. Land Use

This criterion reflects the spatial requirements of hub components, translated into a one-time cost based on the opportunity cost of land. It accounts for the physical footprint and associated spatial planning constraints of infrastructure deployment.

9. Governance and Coordination Burden

This category represents both one-time transaction costs (e.g., contract negotiation, legal setup) and recurring coordination costs (e.g., data exchange, compliance monitoring). It reflects the institutional effort required to establish and operate the assets.

Table 6, Stakeholder value perception

Stakeholder	*What They Want*	*What the EH Provides*	*How This Is Reflected in the Model*	*How This Informs the MCA*
Grid Users	- Guaranteed energy access - Monetization of flexibility - Business continuity	- Access despite congestion - Revenue from curtailment/storage - Operational security	- User-specific load profiles - Curtailment costs & thresholds - Storage behavior	- Energy access criterion - Cost-based curtailment valuation - Innovation potential
Grid Operators	- System reliability - Cost-effective congestion	- Offer perspective to grid users - Deferred grid upgrades	- Time-dependent capacity constraints	- Feasibility scoring (maakbaarheidsgat) - System efficiency

	management - Transparency in load	- Coordinated usage (GTOs/ATOs) - Flexibility visibility	- Group contract modeling	- Transaction cost inclusion
Governments	- Climate goals - Economic development - Energy equity	- Accelerated electrification - Emission reduction - Spatial flexibility	- Broader system impacts framed in context - Indirect benefits not modeled directly	- Land use, employment indicators - Strategic and policy alignment

4.1 Interview Conclusion

Expert interviews revealed divergent priorities among grid users, grid operators, and government actors. Grid users prioritized their energy access, business case and supply reliability, grid operators prioritized grid constraint compliance, system efficiency and long-term grid management, and government actors prioritized sustainability, economic development, and local political ambition. These priorities shape the quantitative model structure and multi-criteria analysis. For example, time-varying constraint limits and a user-driven curtailment mechanism are included to reflect users' compliance-driven concerns, while efficiency and planning objectives govern longer-term system parameters. Likewise, MCA criteria and weightings are calibrated to balance reliability, cost-efficiency, and sustainability as emphasized by each stakeholder group. In Chapter 6, these themes are operationalized into a decision-support framework that combines the quantitative model, presented in Chapter 5, and the MCA to evaluate alternatives consistent with stakeholder priorities, ensuring each perspective is explicitly represented in the analysis.

5 Energy Flow Model

This chapter presents the energy hub simulation model, designed to assess flexibility options alongside grid expansion. The simulation model quantifies the system-level impacts of flexibility measures within an MCEH such that they can be used in the MCA. It evaluates how a predefined mix of storage, conversion, and curtailment compares to conventional grid reinforcement. Section 5.1 (Verification) tests the model's logic and input consistency. Section 5.2 (Validation) evaluates the model's accuracy and real-world relevance through a case study. Section 5.3 (Model Behavior and Outputs) illustrates how the model captures energy flow dynamics, the tradeoffs that can be made apparent, and supports the multi-criteria analysis in Chapter 6.

5.1 Verification

Verification ensures that the model adheres to its intended logic and assumptions. This process includes controlled testing of solver algorithms and cross-referencing outputs with expected results.

Input consistency

The first step is to confirm that grid users' loads are correctly summed and retrieved. To verify this, only the grid point and users are entered into the model. The "grid load" output should match the sum of individual user loads, while grid constraints and prices should align with the input grid profile. Next, the curtailment function is tested. Grid capacity is adjusted to create scenarios where total user load exceeds available transport capacity. The required flexibility is calculated as the difference between available transport capacity and total load, with the negative value reflecting the expected reduction in grid load after curtailment.

Curtailment

Curtailment is applied based on user-defined curtailment capacity, a variable ranging from 0 to 1, indicating the percentage by which a user's transport needs can be reduced. This is computed as "curtailment_cap * current user load". Curtailment is prioritized by cost, ensuring that the cheapest flexibility options are utilized first.

Name	Curtailment cap	Curtailment Cost €/kWh
A	30%	2
B	50%	0.7
C	10%	30
D	0%	-

The curtailment outputs, stored in a dictionary, confirm the expected behavior. Curtailing User B by 46.67 kWh/h reduces the total load from 701.97 to 655.29 kWh/h. Adjusting the curtailment cap for B to 0.1 and lowering the price for A produces the expected changes, demonstrating that the model correctly prioritizes curtailment based on cost and capacity constraints.

Adding a Storage unit

Following the addition of curtailment, an electrical storage unit is added together with a gas storage unit. The parameters *charge_rate, discharge_rate, storage_efficiency, minimum_level,* and *maximum_level* determine storage unit behavior. Storage serves two simultaneous functions: maintaining grid balance within constraints and engaging in price-based energy trading. The energy trading strategy is price-based: storage units are charged when the real-time energy price falls below the average price, and discharged when it rises above. The range between minimum and maximum levels dictates when storage can participate in energy trading while ensuring availability for grid flexibility. If fully depleted, storage cannot support the grid, and if fully charged, it cannot absorb excess energy.

In the model, storage is prioritized over curtailment for flexibility, detailed in figure 18. Storage efficiency determines energy losses and represents round-trip efficiency; for instance, with 90% efficiency, charging 1000 kWh requires approximately 1111 kWh of input. Discharging is assumed to be lossless as storage losses are already accounted for when charging. When storage is used for flexibility, it may temporarily exceed set limits of SOC but will restore balance when grid conditions permit. Non-electric storage, such as gas, discharges when consumed and recharges when generated by a conversion unit.

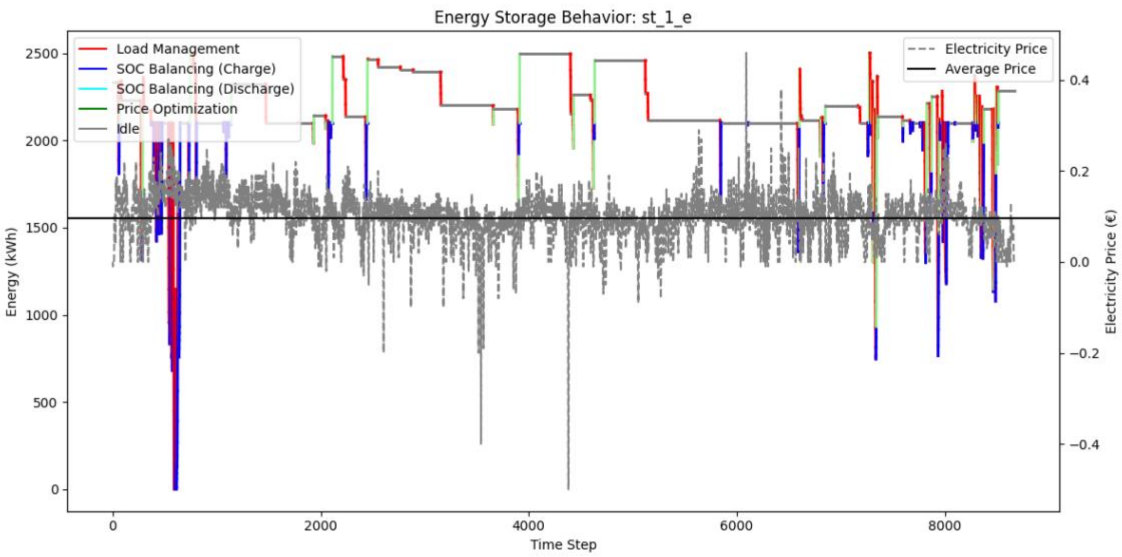

Figure 17, Storage behavior

Figure 18 shows that the electric storage discharges until depleted, after which curtailment is used to maintain grid constraints. When capacity becomes available, the storage immediately recharges following the SOC logic.

Including Conversion units

Gas and heat demand are handled similarly to electricity. The total load across all users is summed, and the corresponding storage is discharged or charged. If the load exceeds storage capacity, energy is drawn from a sink-source object, which functions as an external interface for the hub. Unlike the electrical grid, the sink-source object has no transport constraints. It tracks excess demand or surplus energy, accounting for these imbalances through sink-source mutations.

Next, a conversion unit, such as a fuel cell, is added alongside heat storage. For heat to be an active component, grid users must have a heat load. The model integrates the fuel cell as a dual-purpose unit, supplying both electricity and heat when electric storage is depleted. The generated heat is stored and subsequently used by grid users as needed. When electric storage is exhausted, the fuel cell steps in to maintain power and heat supply. Simultaneously, heat storage is depleted based on grid user demand, demonstrating how conversion units improve system flexibility.

5.2 Validation

Face Validity

The model relies on addition and subtraction to maintain energy balance, as stated in equations 1, 2, and 3, mirroring real-world grid operations. Within a grid ring, energy use is summed, and any imbalance must be addressed by importing or exporting electricity. This principle forms the foundation of the model. The model operates on hourly time steps, simplifying the often-inconvenient mix of kWh and kW in energy calculations. With this approach, 1 kWh/h equates to an average power of 1 kW and 1 kWh of energy or work. Since electricity is typically measured in kWh, while heat and gas are not, all energy values are converted to kWh for consistency. The model's methodology was reviewed and validated by a researcher specializing in the field.

Case Study and Validity Constraints

The case study in Chapter 6 is based on a real-world scenario but includes several assumptions that affect validity and accuracy. Because the model evaluates the energy hub within a future energy system, current prices and usage profiles are not directly applicable. Load profiles and grid constraints were scaled from existing data, if only the modeled grid users can respond to constraints, and if no other flexibility assets exist outside the model. The model assumes that the natural gas network is sufficiently sized to meet energy demand without restrictions. However, limitations in gas or heat distribution networks are not considered. Energy losses are accounted for only when related to storage or conversion processes, while transmission losses are omitted. Storage units and configurations were designed to reflect real-world scenarios, and their performance aligns with expectations. The storage unit successfully manages additional grid demand, and grid capacity sizes match those typical of large industrial connections. Congestion patterns also align with expected seasonal trends, higher demand in January and December leading to capacity constraints on consumption, and peak feed-in constraints occurring in summer months.

Valuation Assumptions and Limitations

The valuation model assumes that electricity, gas, and heat prices are known, whereas in reality, they fluctuate. Historical prices were used as proxies. Curtailment costs (€ per kWh) were estimated as fixed values, though they are highly variable and time-dependent for the grid users. Additionally, curtailment is assumed not to alter future energy usage patterns. While this may be accurate for wind energy, it is unlikely for industries such as bakeries or cold storage facilities, where energy use is flexible, and demand shifts are possible. Finally, the emissions, their potential costs, and inputs and outputs other than energy flows have been overlooked. For example, an electrolyzer requires access to water, while other assets may need cooling facilities. Although these assumptions limit the model’s ability to predict absolute costs, the relative cost structures remain insightful. The results provide an indication of cost distribution and highlight where financial impacts would be concentrated, offering a comparative framework rather than an exact valuation.

5.3 Using the Model to Operationalize the MCA

The energy flow model is primarily an instrument to clarify trade-offs between grid capacity and flexibility, such that various MCEH configurations can be compared with grid expansion.

The simulation converts the tension between grid capacity and local flexibility into explicit, time-resolved trade-offs. It demonstrates the dependency on the temporal coincidence of user loads and available electric transport capacity and returns the interaction between those. By allowing load profiles, asset sizes, and price signals to vary, the model recreates the unique negotiation space of any prospective hub.

Three trade-offs are made explicit by running the same load profiles under progressively larger batteries, broader curtailment bands, and alternative conversion routes. First, peak-shaving is not a linear storage problem: doubling battery size does not halve the residual violations because the congestion hours can cluster around a few extreme hours or days. Second, curtailment delivers rapid relief only when the “right” users, those whose processes coincide with the congestion hours, can scale back. Third, any battery scheduled for price arbitrage loses state-of-charge headroom. This means that if price arbitrage is implemented, it reduces the available capacity that can be effectively used to provide congestion relief, illustrating the tension between private revenue strategies and public-interest congestion relief.

Chapter 6 will further demonstrate how the model can be used and translate the qualitative insights from Chapter 3.

6 Tholen Case Study & MCA

This chapter applies the energy hub simulation model to a real-world case: the industrial estate of Tholen. The experiments are designed to generate the quantitative inputs needed for the MCA and demonstrate, through a range of realistic alternatives on an industrial estate, how structural societal value can guide energy-hub decisions. By varying consumer profiles, network constraints and flexibility assets, key trade-offs are demonstrated. These results, combined with interview insights, show how the MCA framework systematically evaluates and compares hub configurations according to their broader societal value. Section 6.1 describes the case context, stakeholder motivations, and the need for coordinated flexibility. Section 6.2 outlines the experimental design, input assumptions, and alternative configurations. Section 6.3 presents the results of six runs with alternative asset configurations, quantifying their technical performance and cost implications. Section 6.4 summarizes stakeholder-specific trade-offs. Finally, Section 6.5 integrates findings into a multi-criteria analysis to support collective decision-making.

6.1 Case Description

Status Quo

The industrial estate of Tholen consists of 31 participating companies that have collectively committed to aligning their energy demand and supply. By working together, these companies aim to optimize energy usage, jointly purchase and sell energy, and even exchange energy where possible. This collaboration enhances the efficiency of the local electricity grid, ensuring more effective utilization of available transport capacity (Stedin, 2024).

To support these goals, Kenter installed a 2.8 MWh peak battery. This battery helps manage shared grid capacity by absorbing peak energy demand, balancing supply and demand, and stabilizing the medium-voltage grid. It is charged with solar power generated on-site and, if needed, with additional energy from the grid. These initiatives reduce grid congestion and allow businesses to optimize their energy use without disrupting their operations (Firan, 2024).

Context

Shared Grid Connection: Thirty-one participating companies share an MV grid connection, enabling aggregated energy profiles and coordinated capacity planning.
Existing Flexibility Asset: A 2.8 MWh battery installed by Kenter stabilizes energy flows, absorbs peak demand, and enhances local grid utilization.
Energy Profile: Companies rely on electricity and natural gas, with heating needs primarily served by gas systems. Electrifying heating systems (e.g., using hybrid heat pumps) is explored as a future scenario.
Collaboration: Companies A, B, C, and D collaborate to investigate shared solutions for their future heat requirements.
Priority allocation of remaining capacity: Households and "priority" users (e.g. hospitals, new builds) are served first when network capacity is scarce.
Rising residential demand: Continued rollout of rooftop solar and upcoming mandates for hybrid heat pumps (or similar low-carbon solutions) will further increase households' capacity needs.

Residual capacity for businesses shrinks: As priority users absorb more of the available headroom, little or no “left-over” capacity remains for industrial or commercial sites.
Ongoing expansion needs: Even after the 2027 reinforcement, continued economic growth and electrification are likely to trigger further network upgrades.

The Bottleneck

In Tholen’s industrial estate, four companies confront the same medium-voltage grid bottleneck but from different angles. **Company A**, a cold-storage logistics firm, already recycles waste heat and runs almost solely on electricity; its plan to electrify truck fleets was blocked when the operator refused extra capacity. Their cold storage could provide some curtailment flexibility, but nowhere near what is needed for trucks**. Company B,** the estate’s largest energy user, depends on 200 °C gas-fired process heat; while future carbon costs and security-of-supply risks loom, no near-term alternative matches its temperature requirement, so it is exploring hydrogen while balancing profitability against the threat of closure if gas becomes unviable. **Company C** combines rooftop PV with modest demand, leaving unused connection headroom it might lease to neighbors. Yet, it fears sacrificing its own future needs, because energy makes up a small cost share, any forced shutdown would be disproportionately expensive, leaving no curtailment room. **Company D** has deliberately over-contracted capacity and follows a predictable five-day load profile; seeing upside in subsidies and joint projects, it views an energy-hub partnership as a route to higher margins while maintaining its capacity reserve. The regional grid operator, bound by strict unbundling rules, can facilitate but not trade energy. Estate congestion stems from local MV constraints even though the specific high-voltage network often has surplus renewables. Having denied recent capacity-increase requests, the operator encourages a collective Energy Hub that pools spare capacity, coordinates flexible assets, and adheres to agreed ATOs. It will back the hub only if it demonstrably cuts MV peaks, ensures fair curtailment payments, and maintains system stability. Concerns include corporate compliance, misaligned incentives, and uncertain impacts on the higher-level transmission grid. Table 7 depicts the grid user’s contractual capacity and their peak energy use.

Table 7, Stakeholder value perception

	A	***B***	***C***	***D***	***Sum***
Gas Peak (kW)	*-*	*1560*	*259*	*341*	*1923*
Electric peak (kW)	*179*	*567*	*44*	*239*	*915*
Gtv (kW)	*200*	*650*	*150*	*250*	*1250*

Future Requirements

Currently, the estate relies primarily on electricity and natural gas for industrial heating. A shared grid connection aggregates energy profiles across the companies, simplifying capacity planning and increasing operational flexibility. However, as the energy system transitions to CO2 neutrality, an alternative energy source may be required for heating. This case study explores replacing natural gas heating systems with hybrid heat pumps and hydrogen, partially electrifying the heating demand. Encouraged by the success of the 2,8 MWh battery project, stakeholders are eager to explore additional flexibility measures to address future challenges. The largest energy consumer on the estate, referred to here as *Company B*, depends heavily on natural gas for its operations. This reliance has raised concerns as natural gas becomes less viable due to environmental regulations and geopolitical risks. After discussing these concerns with neighboring companies (*"netburen"*), Company A finds that *Company B* shares similar worries about future energy supply and grid capacity. Companies A and B approach the grid operator to request an increase in their grid connection capacity to accommodate electrified heating systems. However, they are informed that the area is congested, making a capacity increase unfeasible. Determined to move forward, Companies A and B reach out to *Companies C and D* to form a collaborative effort. Table 8 summarizes the pain points and energy profiles for each company.

These companies recognize that they lack a clear understanding of their collective energy use and flexibility potential. For instance, assets such as large industrial coolers or production schedules could be leveraged as energy buffers, but their full potential remains untapped. They agree to work together to identify the root causes of their grid constraints: Which usage peaks are driving congestion? Can flexibility be achieved through better coordination or shared assets?

Table 8, Grid User description

Company	***Energy profile***	***Pain-point***	***One-line problem statement***
A – cold-storage & logistics	High electric load for refrigeration and future e-trucks; almost no gas (waste-heat recovery).	Urgent: denied extra capacity for truck chargers.	*"How do we charge our trucks without waiting for grid reinforcements?"*
B – process industry	Largest user; needs 200 °C heat → heavy gas dependence.	Strategic: gas faces cost/policy threats; electrification unfeasible; hydrogen uncertain.	*"How do we stay viable while phasing out natural gas?"*
C – light industry	98 kW-peak PV; actual demand peaks at 44 kW; retains gas boilers.	Wants to share unused grid headroom but fears losing future access.	*"How can we help neighbors without jeopardizing our own capacity?"*
D – manufacturing	Predictable 5-day load; ample contracted capacity.	Sees upside in joining a hub and tapping subsidies.	*"How do we raise profits through cooperation while keeping our capacity cushion?"*

Grid Operator Perspective

- **Mandate:** Reliable supply at least cost; may facilitate but not trade energy/flexibility.
- **Local reality:** Estate congestion is an MV issue, even though the high-voltage grid has surplus renewables.
- **Stance:** Supports an Energy Hub if it demonstrably lowers MV peaks but must police non-firm ATO compliance and fair curtailment payments.

The grid operator is responsible for ensuring reliable electricity transport while maintaining system affordability. The industrial estate is in a region where congestion primarily results from an oversupply of renewable energy on the TSO grid. However, the specific bottleneck affecting the estate lies within the DSO grid. While the transmission system operator may experience excess supply at the high-

voltage level, the industrial estate faces congestion due to excessive local demand. This distinction means that the estate's grid constraints are not directly limited by the TSO, and solutions at the MV level remain a viable option.
Due to its strictly regulated role, the grid operator cannot directly engage in energy supply or flexibility services, limiting it to a facilitating role rather than direct participation.

Municipality Perspective

- **Interest:** Protect jobs, meet climate targets, avoid grid bottlenecks that stifle growth.
- **Involvement:** Zoning, permits, and possible subsidies, yet no direct control over grid investments.
- **Focus:** Align EH plans with regional transition strategy and secure funding; balance long-term policy goals with firms' near-term realities.

The municipality sees EHs as a strategic opportunity to support local businesses, ensure economic resilience, and contribute to sustainability goals. Grid congestion poses a direct threat to industrial activity, local energy access, and future economic growth, making solutions like EHs politically attractive.

6.2 Experiment Design & Data Preparation

The model serves as a decision-support tool that evaluates the effects of different flexibility measures. *The experiments have been designed to demonstrate how different types of flexibility could benefit the Tholen industrial estate as an alternative to the grid reinforcement.*
Table 9 depicts the various configurations and their rationale, which are to be tested in the model. It helps stakeholders answer questions such as:
How do variations in energy usage profiles or grid conditions influence the need for flexibility?
What trade-offs arise between competing measures, such as storage, conversion, and curtailment?

Table 9, Grid User description

ALTERNATIVE ID	FLEX PACKAGE (TECHNICAL / ORGANIZATIONAL MEASURES)	RATIONALE
0	• Existing 2.8 MWh / 1.4 MW battery, operated purely for peak-shaving.	The "do nothing" Alternative. Establishes the *dynamic-grid* baseline; demonstrates that today's storage alone cannot absorb future background-load growth.
1	• Baseline battery plus contractual curtailment (User B up to 130 kW, € 0.70 kWh^{-1}).	Tests a *lowest-capital* option: add an organizational measure to storage so the node stays within grid limits without extra hardware.
2	• Baseline battery• Four battery-electric trucks (264 kW charging 22:00–05:00)• Original curtailment cap (User A 30 %).	Introduces a realistic future load (e-truck fleet) to see whether existing flexibility is still adequate.

2B	• Enlarged battery (5.6 MWh)• Higher curtailment allowance (User A 80 %, € 0.50 kWh^{-1}).	Explores whether *more* storage plus a more flexible contract can mitigate the overloads triggered by alternative 2.
3	• Baseline battery• 1 MW hydrogen fuel-cell CHP, dispatched only when storage is exhausted.	Replaces natural-gas boilers with H_2 conversion, supplying heat and electricity *without* raising electric peaks; tests conversion-based flexibility.
4	• Full grid reinforcement: MV-ring transport capacity raised to 2 MW (no additional local flex assets).	Provides the *benchmark* "build the wires" solution against which all flexibility packages are compared.

The DSO supplied hourly electricity and gas profiles for each hub participant. To comply with the *Netcode Elektriciteit* privacy rules, the data is stripped of metadata and then "blurred" with zero-mean noise to generate synthetic load profiles. The algorithm is documented in Appendix E. To estimate the increase in energy caused by users outside the grid, the Domestic gas use in the feeder area is translated into electric heat-pump load by multiplying hourly gas flows by 1 / COP. The run configurations are further specified in Apppendix F.

6.3 Experiment Execution & Comparative Analysis

Alternative 0 – Dynamic-grid baseline (existing 2.8 MWh battery)
Alternative 0 is the baseline against which all other options are compared. It assumes that external (non-hub) demand on the medium-voltage ring keeps growing, yet the hub relies on its current equipment: a 2.8 MWh battery with a 1.4 MW charge–discharge limit. The battery is used strictly for peak-shaving; it tops up whenever ring load falls below the running average and releases energy during demand spikes. This strategy smooths the load curve and lowers the standard deviation, but it is not sufficient to remain within the grid operating limits. The result underlines that, in a future with rising background demand, the existing battery alone cannot deliver the flexibility required for secure operation. Most importantly, 11 hours occur when loadshedding is required to prevent a power outage.

Findings

- Peak amplitudes and load variance drop, but **11 hours a year still breach the MV limit**.
- As external demand continues to climb, the battery alone cannot provide sufficient flexibility to keep the grid node within its safe operating band.
- Annualized flex costs ~125k
- Total yearly energy costs ~ €1.60 million

Alternative 1 – Dynamic grid with curtailment plus existing 2.8 MWh battery
This option keeps the baseline battery but adds an organizational measure: participants accept a curtailment scheme so that demand can be clipped when the MV-ring approaches its reduced capacity. The aim is to stay within grid limits at the lowest possible capital cost, relying on storage to absorb short-lived peaks and curtailment to handle the few remaining overload moments.

Under the agreed settings, only User B is ever curtailed, and then for a maximum of 130 kW on the worst hour (time-step 613). With User B's willingness-to-pay set at € 0.70 / kWh, total curtailment expenditure comes to roughly € 524 for the year.

Findings

- The combination of battery and limited curtailment **keeps the node within its transport cap for all but events,** a marked improvement on Alternative 0.
- Only **twelve curtailment hours** are required, all borne by a single user, so transaction effort is modest.
- The annual curtailment cost is **≈ € 0.5k**, far below the cost of additional hardware. This indicates that a low-capital, contract-based fix can provide adequate flexibility, at least while external demand remains at the current forecast.
- Annualized flex costs ~ € 126k
- Total yearly energy costs ~ € 1.60 million

6.3.1 Future Energy Hub: load evolution and its implications

The subsequent alternatives extend the baseline hub by adding two distinct demand changes: 1) overnight charging of battery-electric trucks and 2) separately, a hydrogen-fuel-cell, to test whether contractual curtailment, additional storage, or on-site generation can preserve grid compliance.

- **Industrial User B** intends to decommission its natural-gas boilers and adopt a fuel cell. Low-temperature residual heat is to be recovered for internal use and export to neighboring heat consumers. If the full 716 kW average gas load were electrified one-for-one, the site's mean electrical demand would rise from 280 kW to almost 1000 kW, effectively consuming the entire 1 MW transport capacity on the medium-voltage ring and producing peak requirements far above that limit. Complete electrification is therefore infeasible; a gaseous energy source must remain, albeit in the form of H_2 rather than CH_4, in line with a current project in Zeeland (YES!Delft, 2025).

- **Logistics User A** proposes to integrate four battery-electric trucks. Charging requirements amount to 480 kWh per vehicle per day; distributed over an eight-hour overnight window (with a 10% contingency), this translates to an additional 264 kW between 22:00 and 05:00. The corresponding profile has been superimposed on the existing electrical load series.

- **Commercial Users C and D** foresee no material change in their electricity consumption, yet they are willing to abandon individual gas boilers provided that User B's low-temperature heat exports prove technically and economically viable.

These user plans intend to mirror the wider requirements of the future energy system: they raise electrical demand and substitute fossil energy for a low-carbon source. The alternatives are envisaged to reflect the decision-making process and tradeoffs for hubs in the future energy system. The system employs solutions such as energy storage, dynamic demand-side management, and energy conversion to remain within its operational limits (Luo et al., 2014; Netbeheer Nederland et al., 2023, p. 9). The next alternatives test whether these flex assets can keep the MV-ring compliant in the decentralized, renewables-rich system envisaged in the literature.

Alternative 2 – Electric-truck charging (existing 2.8 MWh battery)

User A adds four battery-electric trucks that draw 264 kW between 22:00 and 05:00. No other assets are changed, so the hub relies on the baseline 2.8 MWh storage unit plus the original curtailment limits (30 % for User A). The battery absorbs much of the new load, yet the MV-ring still exceeds its capacity cap for thirteen hours per year, and the extra cycling accelerates battery wear. About 120 curtailment hours are needed, costing roughly € 8400.

Alternative 2b – Electric-truck charging with larger storage and higher curtailment cap
To improve performance, the battery is doubled to 5.6 MWh, and User A raises its curtailment allowance from 30 % to 80 % while accepting a lower curtailment price of € 0.50 /kWh. The larger energy buffer cuts overloads to two hours per year and halves curtailment expenditure to about € 4,200, but residual peaks around hours 600 and 8000 still coincide with low grid availability, making grid overload inevitable and questioning the economic case for the extra € 1.26 million battery module.

Findings

Metric	Alternative 2	Alternative 2b
Certainty of no curtailment	*0.986*	*0.994*
'Not-ok' hours per year	*13*	*2*
Annual curtailment cost	*€ 8 371*	*€ 4 166*
Annualized flex costs	*€ 130K*	*€ 245K*
Total yearly energy costs	*€ 1.68 million*	*€ 1.79 million*

Even with an enlarged battery and a more flexible curtailment contract, the hub cannot eliminate all violations, which makes these configurations unviable; marginal returns on additional storage appear limited.

Alternative 3 – 1 MW gas-to-power fuel cell with heat recovery
User B uses hydrogen as a replacement for natural gas, and a 1 MW fuel-cell combined-heat-and-power unit is installed, choosing conversion over full electrification because that would raise electrical demand beyond the MV-ring limit. The fuel cell runs only when the existing battery is exhausted, and curtailment would otherwise be required. It supplies electricity, meets all low-temperature heat needs, and exports surplus heat to Users C and D. Additional hydrogen is therefore consumed, but no new electric peaks are imposed on the grid. The price of flex now is ~ € 192K annualized, with total energy costs being highly sensitive to hydrogen prices. Assuming a price equivalent to that of natural gas at ~0.14 cents per kWh, the total costs are € 1.52 million.

Findings

- 0 breaches of the MV limit
- No needed curtailment
- Hydrogen replaces natural gas usage, reducing supplied gas energy by 20%.
- Very sensitive to gas prices
- Annualized flex costs ~ € 192k
- Total yearly energy costs ~ € 1.5 million

The fuel costs dominate in comparison to the transport costs for all energy sources. The total yearly energy costs decrease because of the use of residual heat and a decrease in gas usage.

Alternative 4 – Full grid reinforcement (2 MW transport capacity)
This option ignores timing constraints and assumes the DSO upgrades the medium-voltage ring so that every future load can be met electrically.

1) Heat load for domestic heating: Assuming a low outside temperature and a coefficient of performance (COP) of approximately 2, the heat load, when translated into electric load, would be equal to 1/COP ≈ 50%.
2) Industrial heat demand: Assuming the gas system operates at 75% efficiency and the alternative electric heating system at 95% efficiency, the corresponding electric load would be (75/95) ≈ 79% of the gas demand (Qu et al., 2014).

Because the participants already share a single hub connection, the grid-upgrade costs are incurred only once:

- **Up-front investment**
  - Connection fee (*aansluitkosten*): ≈ € 80,000
  - Customer substation (*klantstation*): ≈ € 160,000
  - **Total Grid Investment Costs**: ≈ € 240,000

- **Recurring annual charges**
  - Fixed connection charge (*periodieke aansluitvergoeding*): ≈ € 2 000 yr^{-1}
  - Fixed transport tariff (*vastrecht*): € 230 $month^{-1}$ ≈ € 2 760 yr^{-1}
  - Variable transport tariff: € 3.79 kW^{-1} $month^{-1}$ × 1 000 kW ≈ € 45 480 yr^{-1}
- **Total annual cost**: ≈ € 50 000

These figures cover the entire hub; no additional connection or transport tariffs are charged to individual users. Most of the lower total energy costs result from the decreased energy demand, as heat pumps are more efficient. Annual gas-connection fees and the operating costs of flexibility assets would also disappear, but each participant would face significant retrofit expenses such as high-capacity heat pumps, building insulation, and process modifications to operate fully on electricity. To put the grid-upgrade bill in context: at 2023 power prices, the hub already spends about € 1.1 million per year on electricity. Spreading the € 240,000 up-front investment over 15 years at a 3 % discount rate adds roughly € 70,000 per year, small relative to the energy bill, which is far more sensitive to market-price swings. Financially, that annualized € 70k is therefore the benchmark that the flexibility alternatives must beat.

Findings
- No curtailment
- No grid overload
- Electrification reduces total energy needs

Grid expansion provides perfect technical compliance but at the expense of potential knock-on congestion at higher voltage levels; it represents the benchmark against which the flexibility options in earlier alternatives must be weighed.

6.4 Stakeholder Evaluation

The DSO is concerned solely with transporting electricity and gas; it does not sell the energy itself. For most customers, these network charges are relatively small, between 6 % and 13 % of the total energy bill, so swings in wholesale power or gas prices dominate the overall cost picture (Netherlands Authority for Consumers & Markets [ACM], 2024; Statistics Netherlands [CBS], 2025).

Grid users do not differentiate between energy costs stemming from infrastructure or energy prices; they consider the total final energy cost charged to them, which includes both transport and energy prices. Importantly, the societal cost of congestion is omitted. This cost structure shapes each stakeholder's incentives. *Company A* can electrify its truck fleet only if a new power source or additional transport capacity is connected to the ring. *User B* faces the same hurdle, but at a much larger scale; its vulnerability to hydrogen price and not yet built H_2 infrastructure is consequently higher. *Firms C and D* hold generous transport contracts, so they feel no immediate pressure. Yet, they benefit indirectly if other users' flexibility prevents curtailment orders or loadshedding that would ripple through the ring. For the DSO, the rising background load on the MV ring means that it must still honor existing transport entitlements. If reinforcement lags, the operator may have to install temporary "emergency" assets such as diesel or gas generators delivered on flatbeds, such as the six units recently deployed on Walcheren (Omroep Zeeland, 2024).

Municipal authorities, in turn, have a dual mandate: They must safeguard a reliable supply for protected consumers while preserving the industrial base that provides jobs and tax revenue.

From a purely financial standpoint, a full grid upgrade amortizes to roughly **€ 70,000 per year**, considerably cheaper than the **€ 125,000–€ 245,000 per-year** range for batteries, curtailment payments, and fuel-cell operation. Yet that upgrade cannot be delivered overnight. Flexibility measures are therefore valuable as they "buy time" until reinforcement is completed. Tholen's existing 2.8 MWh battery exemplifies this logic: it is worthwhile precisely because the reinforcement is only expected in 2027. The proposed fuel cell offers a similar bridge, but its long-term viability hinges on hydrogen achieving cost parity with electricity; fuel, not transport, is the dominant component of operating expenditure.

The fuel cell's structural value is adding a dispatchable, non-electrical energy source that continues to furnish flexibility after the MV-ring is eventually reinforced. Since fuel costs dominate operating expenditures, its economic viability rests on hydrogen reaching price parity with electricity. This is exemplified by Figure 19, where energy prices are varied[7]. Low energy costs and the preservation of

[7] The energy prices have been varied according to reports by PwC (n.d.), VEMW (2024), and the Autoriteit Consument & Markt (n.d.), from which the expected highest and lowest values have been taken. The goal is to demonstrate that Alternative A4 is less sensitive to energy cost variations while remaining the top contender.

cheap natural gas would outcompete A4, which otherwise yields the lowest energy cost.

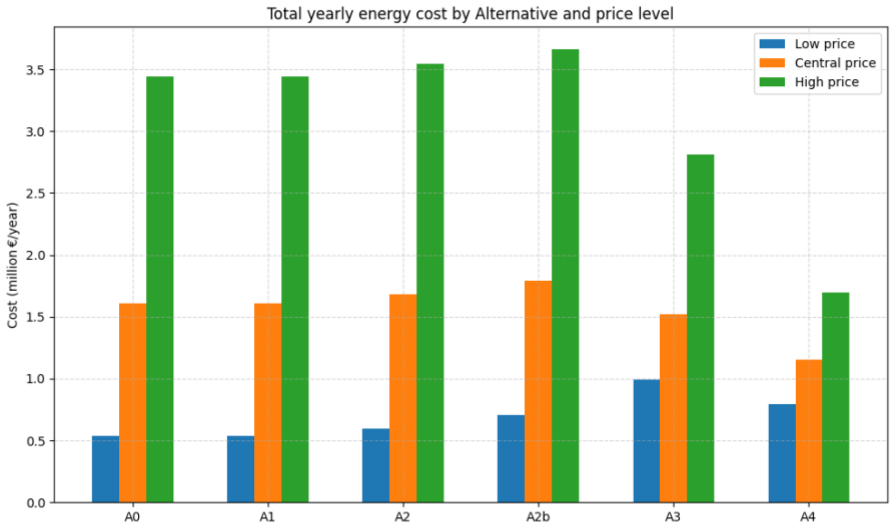

Figure 18, Variation of yearly energy cost across alternatives and price levels

The figure shows how total annual energy expenditure responds to low, average, and high energy price assumptions across alternatives A0–A4. While A4 performs best at high prices, its advantage diminishes under lower price conditions—especially if cheap natural gas remains available. This underscores how fuel price assumptions critically affect the viability of hydrogen-based solutions like the proposed fuel cell.

6.5 MCA Outputs & Experiment Conclusion

Three configurations are possible while respecting the grid constraints: A1, A3, and A4. Grid expansion, A4, outperforms the other options in 9 out of the 11 criteria.
Appendix G contains the estimations used in the MCA and the non-normalized table. Table 10 presents the normalized scores where each alternative has been compared on their relative performance to the best scoring option on that criterion.

Table 10, Normalized MCA output table

Criterion	Normalized Scores					
	A0	**A1**	**A2**	**A2B**	**A3**	**A4**
Grid-Constraint Compliance	0.15	1.00	0.00	0.85	1.00	1.00
Supply Reliability / Business Continuity	1.00	0.94	0.00	0.57	1.00	1.00
Congestion Cost / Time Until Measure	0.00	1.00	0.60	0.60	0.00	0.60
System Impact	0.25	0.50	0.00	0.00	0.75	1.00
Net Annualized System Cost	0.68	0.68	0.68	0.00	0.28	1.00
Total Energy Cost	0.15	0.15	0.00	0.00	0.47	1.00

Resource Footprint	0.67	0.67	0.67	0.00	0.33	1.00
Land Use	0.67	0.67	0.67	0.00	0.33	1.00
Governance & Coordination Burden	0.67	0.67	0.33	0.33	0.00	1.00
Average	***0.47***	***0.70***	***0.33***	***0.26***	***0.46***	***0.96***

Normalized MCA scores across alternatives. Each criterion is normalized on a 0–1 scale, where 1 indicates best performance. Indicators are derived as direct (e.g., grid constraint violations), indirect (e.g., monetized costs of curtailment or energy use), or deduced (e.g., qualitative or estimated impacts like governance burden or land use). The average row provides an unweighted mean score per alternative.

The primary trade-off is time versus cost. Out of viable options 1, 3, and 4, grid expansion stands out for meeting all criteria except for the time it takes to implement. Short-term flexibility options like adding batteries and curtailing energy use or installing a 1 MW fuel cell have higher annual costs than a permanent grid upgrade. Only adding curtailment as a measure (A1) would realistically be operational before the expected grid reinforcement is in place.

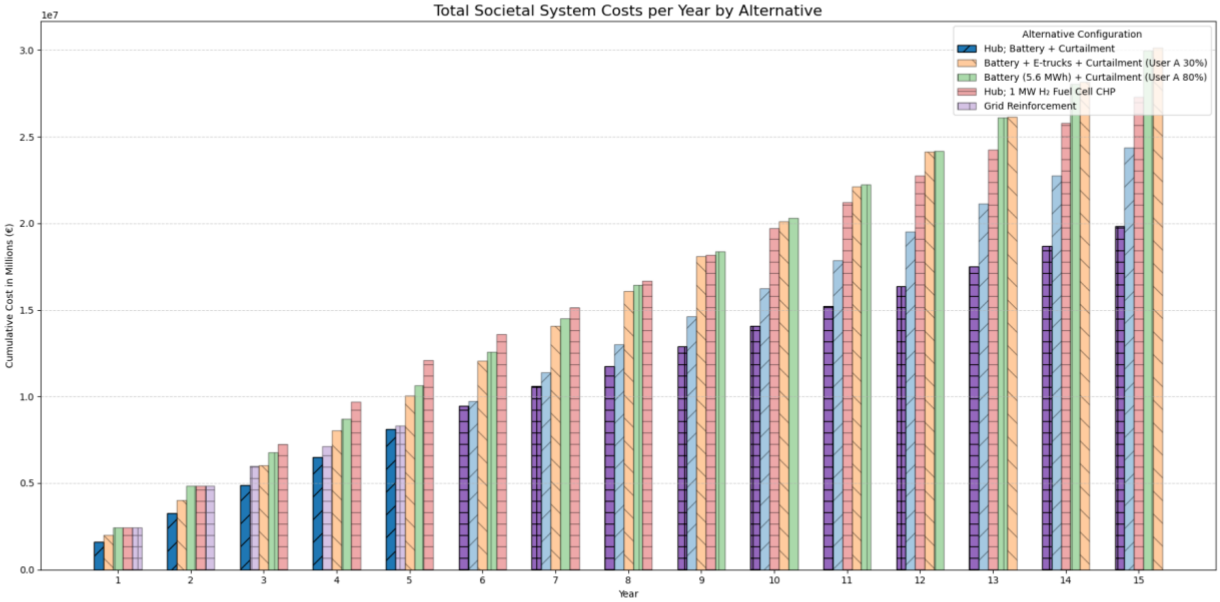

Figure 19, Societal Costs Over Time

This figure presents the total system costs per year across various alternatives, including configurations with batteries, curtailment, and conversion units. Costs are sorted by the cheapest alternative per year, illustrating how different flexibility strategies affect long-term societal expenditure

Figure 20 suggests that using curtailment until grid reinforcement is in place yields the lowest societal cost. While the congestion costs are assumed to be static, they will likely rise over time, only underlining the urgency of tackling grid congestion. This figure also highlights the high cost of inaction and insufficient transport capacity. Relating back to the theme of structural societal value, grid reinforcement is clearly the preferred option; however, the temporary congestion costs may be so substantial that they necessitate the use of costly electric storage or large indemnification budgets. using a joint strategy where storage and a curtailment contract are replaced by grid reinforcement when it becomes available, as shown in Figure 3 in the executive summary, would lead to the lowest societal cost.

Energy hubs reduce or postpone, but do not eliminate, the eventual need for extra transport capacity. Looking ahead, the same hubs could evolve into larger “flex interfaces” that provide the demand-side agility required for deep solar- and wind penetration. However, there is a risk: locations where hubs are currently being implemented due to limited transport capacity may also hinder the deployment of flexibility beyond the local congestion area for the same reason. An approach would be to first address local congestion with flexibility assets while simultaneously reinforcing capacity. This would allow flexibility to later be used to manage generation mismatches at higher network levels, ultimately linking back to the broader societal value of EHs.

7 Discussion

This research investigated the structural societal value of (MC)EHs in industrial estates for the future energy system. The analysis indicates that while EHs effectively provide local flexibility and short-term congestion relief, their broader, systemic value is highly context-dependent, hinged critically upon the specifics of the hub, such as load profiles, energy requirements, and local grid constraints. Hubs, defined as organized flexibility in the MV-grid, provide exactly that as a structural value. Flexibility is an expensive method of reducing the required transport capacity. The value of flexibility beyond congestion depends on the requirement for flexibility for integrating renewables in the future energy system, not optimizing transport, or postponing grid reinforcement.

7.1 Summary of Key Results

The analysis highlights systemic misalignments in energy hub development, shaped by differing stakeholder goals, timelines, and value frameworks. These misalignments collectively complicate consensus and efficient implementation. These misalignments are not merely operational but reflect diverging definitions of value, goals, and planning timelines among actors.

Three core misalignments emerged from the interviews: differences in perspectives, ambitions, and timelines, highlighting the fragmented nature of energy hub development and the systemic barriers to consensus. Each misalignment reflects a deeper structural issue: stakeholders define value differently (perspectives), prioritize engagement for different goals at different moments (ambitions), and operate on fundamentally misaligned planning horizons (timelines). These divergent views highlight that the challenge is not simply whether an EH "works," but whether it works in a way that aligns with each actor's rationale, something that often fails to account for broader societal value. By including various values that are supported by the stakeholders, the method is not stakeholder-specific. Grid users primarily seek reliable energy access, operational continuity, and, where possible, revenue opportunities from flexibility, modeled through curtailment costs, user-specific demand profiles, and storage behaviors. Grid operators aim to manage congestion cost-effectively while maintaining grid integrity, viewing EHs as tools to defer reinforcements, reduce peak stacking, and coordinate flexible loads, insights reflected in the model's dynamic capacity constraints. Meanwhile, governments pursue broader societal goals such as emissions reduction, economic development, and regional energy equity. These differing priorities shape how each actor evaluates the trade-offs of flexibility versus grid expansion.

Hubs are not without burden; they shift part of the system-balancing responsibility onto grid users through collective agreements, such as non-firm ATO contracts. These agreements internalize flexibility, expose users directly to the physical limits of medium-voltage networks, and increase contractual complexity and coordination demands. Moreover, for grid operators, adopting EHs introduces additional planning responsibilities, risks, and operational duties beyond their traditional scope. Successfully managing EHs thus requires specialized technical expertise, effective stakeholder coordination, and active operational management, resources that may not always be readily available.

An MCA was applied to compare the suitability of EHs versus traditional grid expansion. This approach compares Hubs against grid expansion based on multiple markers that capture both private and public value. Nine criteria, depicted in Table 1, aimed to capture structural societal value and were operationalized and compared in the Tholen case study.

Grid reinforcement outperformed all alternatives on all criteria, except curtailment, which could be implemented quicker, resulting in lower congestion costs until the grid reinforcement was in place. The grid remains cheaper, simpler, less resource-intensive, and easier to manage than EHs. EHs impose significant transaction costs, operational complexity, governance shifts, and coordination challenges among users, creating dependencies not present in traditional grid infrastructure. While EHs can rapidly relieve congestion and enhance energy autonomy, this benefit diminishes following eventual grid reinforcement.

Ultimately, the broader economic context influences the attractiveness of EHs. Transportation and network costs are relatively low compared to energy prices, influencing the cost-benefit perspective of EH adoption. Nevertheless, the future energy system's reliance on increased renewable integration will significantly drive investment in transmission infrastructure (ACM, 2023; International Energy Agency [IEA], 2023). Given that fuel costs dominate operating expenditures, the economic viability of solutions such as fuel cells strongly depends on hydrogen achieving price parity with electricity.

7.1.1 The Interpretation of Results

This research highlights why current evaluation and decision-making practices often fail to support effective EH deployment. Two key gaps emerged:

1. **Evaluation gap:** Stakeholders predominantly see energy hubs as tools for congestion relief and independently assess them based on the value provided to them by the hub*, ignoring externalities.*
2. **Decision-making gap:** While models do exist, they are not particularly effective as decision-making tools because of the *disconnect between their assumptions and real-world decision-making constraints.*

Initially, it was hypothesized that technical models are not necessarily intended as decision-making tools. The wicked problem nature of energy hubs may have led stakeholders toward implicit evaluations primarily centered on congestion relief. The Tholen case study, which applied a new evaluation method to address these gaps, produced similar results. Grid reinforcement remained preferable to flexible solutions for increasing transport capacity. Flexible assets demonstrated their primary value as interim congestion solutions but underperformed compared to structural grid reinforcements in delivering long-term societal value. The similarity of outcomes between the new evaluation method and the existing approach raises the question: *Are congestion and the timing of expected grid reinforcement indicators for locating hubs, if societal value is the primary goal?*
The case study reinforced that flexible assets in hubs provide interim value only until structural reinforcement occurs. Therefore, potential hubs should be assessed not only on immediate value but also on their longer-term role. However, capacity users currently see them primarily as temporary solutions, and maybe rightly so.

These insights contrast with grey literature, where both the operators and government typically portray energy hubs as broadly beneficial and central to future strategies. This discrepancy may arise from the lack of a unified definition of energy hubs, as confirmed by interviews conducted during this research. Consequently, practical hub implementations might use definitions tailored specifically to their particular applications. Interestingly, societal benefits (e.g., emissions reductions), frequently emphasized in grey literature and by interviewees, were notably absent from traditional grid expansion decision frameworks, nor used in the implicit stakeholder evaluation framework. Experts argued that these benefits are already embedded in existing regulations. This discrepancy raises important questions: *Are emissions and similar parameters included in hub models primarily to enhance perceived value? Should these parameters be equally considered in regular grid expansion analyses, or should they instead remain directly tied to energy production sources?*

7.1.2 The Implication of the New Evaluation Method: Clarify the Goal of Flexibility

The MCA proposed in this study was intended as a more comprehensive evaluation framework, yet its superiority and the suitability of its indicators cannot be assumed. Choosing evaluation criteria is itself a design act: it determines which system properties receive attention and therefore shapes the system that ultimately emerges. When new criteria are adopted, they reveal weaknesses in the existing system; the system adapts and, in turn, prompts further revision of the criteria. Because socio-technical systems evolve through the interplay of stakeholders, technology, and governance, ill-considered criteria may lock the transition into sub-optimal pathways and cause delays that are costly to reverse (Chappin & Blomme, 2022).

Thus, the method's strength lies in explicitly stating the criteria and substantiating them through interviews and literature, integrating technical and institutional realities. This offers clearer insight into the systemic value of flexibility, creating a more accurate perception of the problem and greater certainty and perspective.

Critically, this research highlights that the multi-carrier energy hub's structural societal value, when compared to grid expansion, lies primarily in enabling the integration of renewable energy sources, rather than simply serving as an alternative to grid reinforcement. Although this renewable integration value wasn't quantified in this study, it potentially surpasses mere congestion relief in specific contexts. However, it's crucial to distinguish between flexibility designed for renewable integration and flexibility used to address transport constraints.

A hub cannot simultaneously resolve grid congestion and support renewable integration if these needs overlap. For instance, flexibility resources allocated to balance renewable energy supply and demand become less available for managing transport capacity shortages. In simple linear networks, transport demand directly matches energy demand, as energy travels directly from generation to consumption. However, real-world networks have complex interconnected topologies where multiple sources on various grid levels feed various destinations. Using flexibility located in one area to manage renewable oversupply in another distant location occupies significant transmission capacity, limiting its availability for other purposes. Conversely, co-locating flexibility with renewable generation reduces network load, maximizing flexibility effectiveness.

7.1.3 Limitations

This research comes with several limitations. In the greater context, the findings suggest that the structural value of hubs lies in the integration of renewables. Yet, no renewable generation was included in the Tholen case study as it fell outside the chosen MV grid point.

The methodological limitations are as follows: First, future energy prices and other external variables are inherently uncertain. To manage this, the simulation uses parametric inputs like alternative-based price bands. Second, although purposive, cross-sector sampling was used to include a diverse set of stakeholders, certain niches may still be underrepresented. The simulation model is intentionally non-optimizing to avoid overstating precision. This choice supports transparency but also means that outcomes remain sensitive to specific load profiles, especially in smaller energy hubs, where large individual users can have a disproportionate effect. Fourth, the selection of MCA criteria inevitably involves some researcher judgment. The generalizability of the case study is also limited: the focus is on a congested medium-voltage ring in Tholen, and findings may not directly transfer to other voltage levels or grid topologies. Additionally, the model assumes fixed user behavior and transport requirements and uses historical data to project future energy prices. These assumptions may not fully reflect evolving market dynamics. The interview methodology also has limitations, including potential researcher bias, framing effects, and sampling bias. These were mitigated through open-ended questioning, real-time clarification of terms, anonymization, and cross-validation with external researchers. Interview insights were further checked against gray literature, policy documentation, and peer-reviewed research. Despite these efforts, some methodological constraints remain. Lastly, the valuation model uses fixed assumptions for price and curtailment costs and does not account for their variability or the potential impact of curtailment on future energy use patterns. Non-energy inputs and outputs, such as water or cooling, were also excluded. As a result, the model offers useful insights into relative cost distributions, but absolute cost levels should be interpreted with caution. Future research could build on this work by simulating different renewable sources and their connections to the grid to validate and quantify that the structural value really comes from incorporating renewables.

7.2 Future Research: Determine the Role of Hubs Within Systemic Flexibility

The structural value of multi-carrier energy hubs (MCEHs) lies in their ability to provide flexibility. However, the benefits of this flexibility strongly depend on local conditions, particularly the network topology and availability of renewable energy. As outlined in Chapter 2, the future energy system will differ significantly from today’s system. Since this study's findings are based on a single case, broader validation is needed.

Future research should focus on identifying the conditions under which hubs offer net societal value. Optimization studies can help define these boundary conditions and shift the strategy from fitting a hub to a case, toward identifying optimal hub configurations first and then finding matching real-world locations.

Renewables differ from traditional energy sources in cost structure. They reduce marginal costs but increase system and network costs, which comprise a growing share of the total energy cost. This shift demands new thinking about cost allocation and incentives.

Governments play a key role in steering the energy transition. Whether grid users, motivated by clear cost-benefit logic, or operators, constrained by regulation and risk aversion, take the lead, policy must adapt. Today's cost structures and regulatory frameworks often do not align with broader societal goals. It brings up urgent questions about how to allocate energy and network costs and what part public institutions should take in creating fair and effective transition paths.

This raises critical questions for future policy discussions: *How should network and energy costs be distributed fairly, and what specific role should the government play in supporting the energy transition through tariffs and regulatory frameworks, protecting societal interests?*

Future work and policy questions

- **Locate the sweet spot.** Use optimization studies to identify grid topologies and renewable mixes where hubs outperform dedicated upgrades, then seek real-world cases that match those conditions.
- **Re-design tariffs.** As renewables push system and network costs to a larger share of the energy bill, tariffs and incentives must steer private choices toward solutions with the highest societal value.
- **Clarify governance.** Determine when full grid-operator control over flexibility assets would be more efficient than user operated hubs and how regulation can enable that when warranted.
- **Fair cost allocation.** Debate how network and energy costs should be shared among users, operators, and government so that the energy transition's benefits and burdens remain aligned with societal interests.

8 Conclusion

Answer to RQ: ***The structural societal value of hubs beyond congestion is the ability to provide flexibility for renewable integration.***

However, multicarrier energy hubs on industrial estates offer *structural* societal value only when they deliver the location-specific flexibility required to integrate variable renewables**.** By coordinating local loads, storage, and generation, they can sharpen the dimensioning of network assets and, in specific contexts, postpone or narrow grid reinforcements. Where the renewable-driven need for flexibility is modest, straightforward grid expansion remains cheaper, simpler, and less risky.

From a systemic perspective, hubs are best seen as a transitional tool. They buy time during congestion but don't replace the need for structural capacity. Since society ultimately pays, whether for flexibility assets or grid upgrades, choices should be based on total system cost. That hubs currently only emerge under acute congestion suggests they lack broader appeal under current rules. Their value lies in adaptability: they offer short-term relief, enable coordination, and create breathing room for better planning. Still, in terms of capacity and cost, they remain secondary to grid reinforcement.

This research contributes academically by addressing the limitations of purely technical modeling approaches. It integrates societal value considerations into decision-making, enabling a more holistic evaluation of energy hubs. The approach is transparent, context-sensitive, and grounded in real-world practice. The model is designed for adaptability, allowing for application to various case studies. The use of clearly defined criteria helps identify and assess societal value dimensions, providing a structured method to evaluate the systemic societal relevance of energy hubs.

8.1 Practical Implications: Translating into Systemic Value

- **Hubs do not replace structural grid capacity**: In the long term, hubs are not substitutes for grid expansion. Their role is complementary, not foundational.
- **Congestion costs are real and rising**: Delayed reinforcement leads to high societal costs, such as curtailment, emergency generators, or business disruptions. These justify interim flexibility measures.
- **Hubs add value when congestion is acute**: In cases where grid reinforcement is years away, hubs that offer flexibility at a low sunk-cost premium are valuable for "buying time" and avoiding outages.
- **The integration of renewable energy sources represents a significant opportunity for hubs**: When strategically positioned, hubs can transition from mere instruments for alleviating local congestion to essential nodes for the integration of solar and wind energy.
- **Stakeholder alignment is essential**: The value of hubs depends on local context—existing contracts, municipal goals, industrial needs, and DSO limitations. Hubs succeed when they align system needs with user incentives.

Seeing hubs merely as congestion fixes underestimates both their potential and their limitations. Their value lies in strategic deployment: managing peaks, bridging grid delays, and laying the groundwork for renewable integration. Yet they remain a transitional measure. The structural solution, reinforced grid infrastructure, still outperforms hubs in all structural value criteria. What hubs do offer is time, coordination, and optionality in a system that needs all three.

8.2 Reflection

Here, I present a reflection on the research method and my personal experience. The reflection on the method details the evolution and my perception of the research methodology, followed by the study's role within academia. The personal reflection describes my experience and lessons learned during the research.

8.2.1 Reflection on Research Method

The research process evolved significantly over the course of the project. I originally envisaged a methodology in which stakeholder interviews would establish evaluation criteria that a simulation model would then quantify. As the work progressed, both the methods and their respective roles shifted in response to new insights and practical constraints.

The central method became the multi-criteria Analysis (MCA). The difficulty lay not in executing the MCA itself but in discerning and formulating the appropriate criteria. Achieving this required an iterative combination of interviews, modelling, and supplementary tools to ground the MCA in empirical reality.
The underlying idea appeals to me: just as energy carriers can be orchestrated "intelligently" to meet objectives, research methods can also be combined to address multifaceted questions. Like real-world system integration, however, implementation proved challenging.

Initially, I assumed the interviews would serve only to supply criteria for the model. They proved far more illuminating. Beyond the criteria, they revealed how diverse actors frame decisions in energy systems, prompting a fundamental redesign of the model's purpose and structure.

Organizing the interviews was unexpectedly straightforward, owing largely to Stedin's support and the perceived urgency of the topic. A recurring challenge, however, was that interviewees tended to answer from the vantage point of their own projects rather than from the perspective of energy hubs as a systemic concept. I mitigated this by explicitly asking each participant to define "energy hub" and specify the context on which their answers were based.

The interaction among interviews, criteria, and modelling evolved into a feedback loop: interview insights shaped the model; the model clarified what could be measured; subsequent interviews refined both. Although this added complexity, it enhanced the relevance and robustness of the research.

A further observation concerns the field's rapid development. Literature, practical insights, and implementation strategies are shifting quickly. While energy hubs are celebrated for potential efficiency gains, in practice, they are deployed mainly for congestion relief. This divergence between theory and practice underscores the need to align research and models with real-world decision-making.

My perspective on modelling changed accordingly. I began by viewing models as optimization engines delivering the "best" solution. Over time, I recognized that no model fully captures reality and that expecting prescriptive answers is misplaced. A model must be purpose-specific. In this project, it evolved into a structured thinking aid rather than a prescriptive tool.

Developing the model proved more manageable than anticipated. A modular architecture allowed individual components to be validated and adapted separately. Iteration focused the model on a clear objective and informed deliberate choices about scope. The model was customized to the real-world data output format used by operators, facilitating the utilization of actual data.

My contribution aims to support better decisions, and the interviews confirmed that improvement begins with understanding existing decision-making processes. As with energy systems, designing the future requires comprehension of the past.

Accordingly, my objective is not to impose a single conclusion but to equip readers to draw their own informed judgments. A simplistic takeaway, such as "if grid expansion is delayed, use a temporary hub; otherwise, do not," adds little. It overlooks societal value and focuses only on visible congestion.

One of the pitfalls of my solution-focused approach is similar to that of hubs; I tend to choose methods or solutions without being deliberate in my problem-solving, ignoring the consequences and whether there's a better alternative. The same applies to hubs; they are presently utilized as emergency remedies for congestion. However, in contrast to my method, their expenses are notably higher, and their effects are extensive.

Stating the obvious, a more nuanced message is: "Conduct an analysis before deciding." The outcome may still often be "use hubs for congestion management," but it is now underpinned by explicit reasoning. Situations in which hubs add value through aligned local generation and demand profiles or alternative contractual arrangements for exchanging transport capacity are no longer ignored. Conversely, constructing congestion-focused hubs with the hope they'll serve a purpose for renewable integration seems like an expensive form of optimism.

Although not initially a stated goal, my research expands on the use of societal value to inform investment decisions, which are thoroughly examined in the report "De maatschappelijke kostprijs van netcongestie" by Ecorys et al. (2024). By reviewing their findings, I found that adopting a wider scope for investment decisions is the right approach, which is both encouraging and validating.

"In times of grid congestion, it is important to assess which option is most desirable and entails the fewest opportunity costs. A societal cost-benefit analysis (SCBA), based on the results of this study, can provide greater clarity. Specifically, using the societal cost price of grid congestion, it is possible to determine the cost of not investing in congestion-mitigating measures. Conversely, it also allows for determining the benefits of investing in mitigation. A follow-up study with an SCBA offers insight into which investment choices most benefit society" – Ecorys et al., (2024) translated from Dutch

My methodological preferences prioritize problem-solving over methods. This instrumental application of methods evokes the "engineering toolbox" analogy taught at the TU. An unfortunate consequence is that relevant literature is initially evaluated based on its potential to facilitate the achievement of a specific goal, which sometimes leads to a neglect of the core understanding of what my goal entails in relation to their research. Fortunately, my work occupies a balanced position between a quantitative modeling approach and a qualitative interview review, both of which seek to address each other's weaknesses. However, similar to system integration, this approach necessitates considerable effort and introduces new dependencies and uncertainties.

Finally, situating energy-hub policy in the broader energy-system context is essential. For grid operators, energy transport is a critical concern, but it represents only a fraction of total system costs. Gains in transport efficiency can be meaningful, yet they may be dwarfed by factors such as energy-price volatility experienced by end-users. This reinforces the imperative to embed energy-hub policy within a systemic perspective.

8.2.2 Reflection on Personal Experience

Here, I present my personal experience regarding the research process. I discuss my experience, lessons learned, and accomplishments based on events I encountered.

Two decisions from which I continue to reap the benefits are choosing a subject I am passionate about and finding the right people to learn from.
Energy system integration has been the guiding theme in both my studies and professional development. From a pure system efficiency perspective, merging systems to achieve better performance is straightforward; reality is not so much. The two professors whom I approached had a technical and institutional background, reflecting the primary axis of system integration to me. The company department where I performed my research is deeply familiar with the subject. Together, they provided guidance, time, experience, and knowledge. While sometimes intimidating, it challenged me to improve, learn, and meet their standards.

The first lesson I learned was to start clear and simple, then add complexity.
After presenting my research proposal, Stedin and my professors suggested refining my question. The suggestions were valid and based on their preconceived ideas regarding my research project, as their experience and expertise shaped their interests and perspectives. Confident that I had struck the right balance, I presented at the kick-off, discovering that merging everyone’s objectives without fundamentally revising my approach was a mistake. Their expertise shaped their expectations, and I found myself caught between honoring that guidance and staying true to my own vision. This has taught me the importance of clear communication, boundaries, and managing expectations. What I will do differently is to start at a clear and simple common ground and then add complexity. This means distilling the project to its absolute core. Hopefully, this common starting point will prevent everyone from filling in their own assumptions and creating their own idea of what the project should be, avoiding trying to merge five different visions.

The second takeaway is to use structure as a guiding method.
What I’m taking forward is placing individual details within a broader context defined by the structure. If details aren’t anchored in the bigger picture, they can easily become distractions. Ockham’s Razor comes to mind, but applying it successfully requires a clear hypothesis, which itself evolves over time. I struggle with structure, both in applying academic theory and in thinking logically. I feel more comfortable with a dynamic, intuitive, and free-flowing approach. That’s why the “agile” sprint method worked well for me, allowing me to move quickly and generate results. However, that freedom came

at a cost. The agile sprints and research process became too unstructured, creating a disconnect for the reader. I had made assumptions, formed ideas, and moved on without detailing the process. This experience taught me that research is just as much about clearly communicating what you've done and why as it is about showing the results and methods. In the future, instead of trying to reverse-engineer a structure after doing the work, I will begin with structure and build up from there. That will help ensure that each step in the process stays connected, for myself and for the reader.

My final takeaway is: Is this a problem that needs solving, instead of first trying to solve it?
For system integration to work, you must know what you are comparing against. To know what to compare, you must be familiar with the systems. As you become familiar with the systems, more complexity becomes apparent, leading to further needed research. The complex nature of system integration presents many challenges, not all of which are equally relevant. When I relate this to my own research process, the same becomes clear. Can I make a sufficiently informed decision based on my information?" This is a pragmatic approach that seeks to balance both aspects. However, much like modeling, interviews, and MCA, it lies somewhere between an art and a method. I have significantly improved in this area, but not without challenge; the challenge is part of the research process, as my professor told me early on, enjoy the process and remember that research is not a linear process." What I take away is: zoom in when needed, zoom out when you can.

While ambition, determination, and goal-oriented focus are important strengths, they can also lead to unintended drawbacks. In my case, they sometimes result in tunnel vision, becoming overly fixated on a specific aspect of the research at the expense of broader reflection. This can compromise objectivity and obscure the original research intent. A key skill I developed during this process was the ability to actively seek external input when facing such challenges. Rather than continuing in isolation, I learned to pause and engage others in reflection. These moments often served as a "reset," allowing me to reconnect with the purpose of my work. Seeking out different perspectives also helped me become more aware of how personal circumstances affect research performance, an awareness that is easily lost when immersed in the process. In this regard, involving others has not only improved the quality of my research, but also ensured a more sustainable and reflective approach. Sometimes, stepping back is the most effective way to move forward.

This journey has taught me the importance of starting from a shared, clearly defined foundation, seeking structured collaboration, and aligning vision with method. Progress, both in research and system integration, requires not only clarity and structure but also reflection, adaptability, and communication

9 Policy Recommendations

Multicarrier Energy Hubs can bridge today's grid congestion and help tomorrow's renewable-integration challenge, but only when each actor sees a clear, credible pathway from short-term congestion relief to long-term systemic value. The Tholen MCA highlights three priorities: decisive governance, targeted flexibility, and fair cost allocation.

9.1 Government & Regulators: Give Direction and Certainty

- **Choose the system end-state and signal it early.** Release a national "flexibility corridor" map that highlights areas where energy hubs should transition into permanent flexible interfaces, and where early network reinforcement with excess capacity is the most cost-effective option.
- **Select a designated area where flexibility for renewable integration will be developed**. By clearly delineating where flexibility for renewable integration will be established beforehand, renewable assets can also be oriented towards connection to those locations. Furthermore, while awaiting the implementation of renewables in those areas, the assets may potentially be used for congestion relief until the renewables and grid reinforcement are in place.
- **Widen the net-operator mandate.** Permit DSOs to procure or even own fast-deployable flex assets when they demonstrably lower whole-system cost—while keeping unbundling rules for energy trading intact.
- **Guarantee procedural speed.** Create a "congestion-mitigation fast lane" for permits covering temporary batteries, electrolyzers and other flex assets.

9.2 Grid Operators: Embed a Clear Economic and Operational Framework

- **Adopt two distinct hub tracks.**
    - ***Bridging hubs***: time-limited EHs that exist only until scheduled reinforcement arrives. Focus contracts on peak-shaving and limited curtailment; depreciate assets over the bridge period.
    - ***Structural hubs***: permanent nodes located where renewables and demand coincide. Prioritize assets that later offer system-balancing value (electrolyzers, V2G fleets).
- **Standardize non-firm Access & Transport Obligations.** Publish template contracts that spell out activation windows, baseline verification, and penalty curves so every participant understands exposure.

9.3 Businesses: Engage Strategically with Hub Flexibility

- **Anticipate the changing price structure of renewable energy.** Increasing transport expenses relative to energy cost changes the exposure to energy price volatility, which will likely increase due to renewable integration.
- **Evaluate your vulnerability to congestion.** Increased electricity transport demand, whether due to climate regulations or operational growth, creates exposure to congestion. Industrial users are particularly vulnerable due to the high costs and limited possibility of using mitigating measures for their use case.
- **Quantify and pool risks.** Negotiate collective curtailment pools so rare high-impact events are shared instead of crippling a single firm. Insurance-type arrangements can cap downside while preserving low tariffs.

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Appendix A: Literature Review

Approach
The Scopus database was queried using the search string: "Modeling AND energy AND coupling AND heat OR electricity OR gas AND grid AND optimization," resulting in 17,901 documents. Filters were then applied to refine the search:

- Limited to Engineering: 9,941 documents
- Limited to Energy: 9,238 documents
- Limited to Environmental Science: 3,433 documents
- Limited to Mathematics: 3,036 documents
- Limited to Computer Science: 2,878 documents

Additionally, language and territory filters were employed:

- English Language: 14,650 documents
- Dutch Territory: 342 documents

From this refined pool, a targeted search was conducted, resulting in 226 papers meeting specific criteria related to modeling, energy, coupling, heat, electricity, gas, grid, and optimization across various subject areas and geographical affiliations. Each article underwent individual evaluation based on its abstract and title for relevance.
Papers proposing modeling solutions for integrated energy systems were included, except for cases significantly differing from the Dutch context, such as islands or regions with limited infrastructure. Policy-centric papers were excluded unless directly related to legislation affecting Dutch territories, and only European, Dutch, and North Sea energy policies were considered. Studies solely assessing singular energy sources or carriers, along with research on energy market integration, were omitted, except for those adopting a socio-technical perspective.

Factors suggesting high relevance include:
- Integration of multiple energy sources or carriers, along with system optimization and energy storage.
- Consideration of sociotechnical dynamics in policy implementation for multi-carrier systems.
- Combination of system integration with energy storage or alternate energy carriers.

Factors indicating limited use are:
- Feasibility studies of singular energy sources.
- Suggestions for further market integration of the electrical grid.
- Research limited to a singular energy carrier or source.

Based on these criteria, 22 articles were selected from the initial pool of 226 for further analysis

Appendix B: Interview Consent Form

Geachte,

U wordt uitgenodigd om deel te nemen aan een onderzoek genaamd ***De structurele waarde van energy hubs***. Dit onderzoek wordt uitgevoerd door **Thibaud Peters** van de TU Delft in samenwerking met Stedin Netbeheer BV.

Het doel van dit onderzoek is om de waarde van een energie hub, wanneer dit niet gebruikt wordt om netcongestie op lossen, te evalueren. Dit onderzoek is onderdeel van een masterthesis voor de studie Engineering and Policy Analysis aan de TU Delft. Dit zal ongeveer 45 minuten in beslag nemen. De data zal gebruikt worden voor het maken en valideren van een energiehub model, waarbij rekening wordt gehouden met de technische en organisatorische belangen en beperkingen van de betrokken partijen in de uitvoering van een energie hub. Uw data zal tevens anekdotisch aangehaald kunnen worden in de onderbouwing van de modelkeuzes. Het model en de beschrijving daarvan zal als thesis gepubliceerd worden op de publiek toegankelijke repository van de TU Delft. Mogelijk leidt deze thesis tot vervolgonderzoek of word deze voor educatieve toepassingen gebruikt. U wordt gevraagd om een aantal vragen met betrekking tot uw bedrijf en energiehubs te beantwoorden, hier bent u vrij uw mening en visie op dit onderwerp te delen.

Voorbeeldvragen zijn:
1) *Wat is uw rol in organisatie X, en welke beslissing bent u bevoegd te maken?* Of
2) *Welke stappen heeft uw organisatie gezet om met netcongestie om te gaan?*

Zoals bij elke onlineactiviteit is het risico van een databreuk aanwezig. Wij doen ons best om uw antwoorden vertrouwelijk te houden. Aan uw data zal een geanonimiseerde code worden toegewezen zoals "Grootafnemer1B" in plaats van uw naam of organisatie.

Alle persoonlijke gegevens worden opgeslagen bij de TUD, op een veilige institutionele opslag, die alleen toegankelijk is voor het TUD-onderzoeksteam. We zullen een anonieme samenvatting van ons gesprek maken, die vervolgens naar u zal worden gestuurd. Mocht u zorgen hebben over de inhoud van de samenvatting, dan bent u van harte welkom om contact met ons op te nemen. De samenvatting zal openbaar beschikbaar worden gemaakt en aan het einde van het onderzoek met Stedin worden gedeeld.

Alle persoonlijke gegevens die tijdens het project zijn verzameld (zoals het transcript en het bewijs van toestemming) worden bewaard voor:

- *Indien er geen paper is: 1 maand na het einde van het onderzoek.*
- *Indien er een paper is: 2 jaar. De audio-opname zal aan het einde van het onderzoek worden verwijderd.*

Uw deelname aan dit onderzoek is volledig vrijwillig, en u kunt zich elk moment terugtrekken zonder reden op te geven. U bent vrij om vragen niet te beantwoorden. Ook heeft u recht op de rectificatie van uw antwoorden.

Appendix C: Interview Summaries

Interview #1: Energy Proposition Manager, 11.1.2024.
Interview #2: Grid Architect, 10.11.2024.
Interview #3: Innovation Consultant , 18.11.2024.
Interview #4: EH Researcher & Consultant, 19.11.2024.
Interview #5: SME Energy Consultant , 21.11.2024.
Interview #6: Expert Hubs & Innovation, 22.11.2024.
Interview #7: Transition Manager Energy Systems, 26.11.2024.
Interview #8: Consultant Energy System SmartGrids , 28.11.2024.
Interview #9: Senior Consultant Strategic Exploration and Innovation, 02.12.2025.
Interview #10 Area Manager DSO, 05.12.2025.
Interview #11: Energy System Strategy Expert, 07.01.2025.
Interview #12: Manager Legal Affairs, 16.01.2025.

Interview #1: Energy Proposition Manager, 1.11.2024

Achtergrond

Doel van het onderzoek:
Het onderzoek richt zich op het identificeren van de structurele maatschappelijke waarde van energiehubs (EH's).
Doel van de interviews:
De interviews hebben als doel om inzicht te krijgen in de percepties en verwachtingen van verschillende stakeholders ten aanzien van energiehubs. Deze inzichten moeten helpen bij het uiteenzetten van verschillen in waardebeleving.
Achtergrond van de geïnterviewde:
De geïnterviewde is sinds januari werkzaam als propositiemanager bij Stedin. In deze functie is hij verantwoordelijk voor het ontwikkelen en opschalen van nieuwe concepten.
Hij heeft een achtergrond in productmanagement en innovatie en heeft gewerkt in sectoren zoals TNO, telecom, en bij ingenieursbureau x.
Rol van Stedin bij energiehubs:
Stedin speelt een faciliterende rol bij energiehubs. Het doel is om bedrijven te ondersteunen in samenwerking op het elektriciteitsnet, congestieproblemen op te lossen, en bedrijven te helpen die geen toegang hebben tot extra transportcapaciteit. Er ligt een sterke nadruk op het ontwikkelen van softe of administratieve energiehubs, die geen directe aanpassingen aan de lokale infrastructuur vereisen. Deze aanpak is gebaseerd op het slim en efficiënter benutten van de bestaande netcapaciteit, zonder grote investeringen in fysieke uitbreidingen.
De geïnterviewde merkt op dat de afgelopen 15 tot 20 jaar onvoldoende in de infrastructuur is geïnvesteerd, wat heeft geleid tot de huidige congestieproblemen. Hoewel het concept van EH's breed wordt gewaardeerd, is het lastig te bepalen hoeveel waarde ze daadwerkelijk opleveren en voor wie deze waarde geldt.

Hoofdvragen

1) Waarom is Stedin betrokken bij een EH-traject?
Stedin ziet energiehubs als een manier om bedrijven te ondersteunen die problemen ondervinden door congestie. EH's kunnen een oplossing bieden voor dit groeiende probleem, wat ook hun waardeperceptie versterkt.
Daarnaast kijkt Stedin steeds meer naar de mogelijke voordelen voor zichzelf:

- **Verminderen van transportcapaciteit:** EH's bieden de mogelijkheid om netcapaciteit efficiënter te benutten, waardoor de druk op het netwerk afneemt.
- **Toegang tot flexibiliteit:** EH's kunnen helpen bij het creëren van een meer flexibele omgang met energie, wat de stabiliteit en efficiëntie van het net ten goede komt.

2) Welke taak moet een EH voor Stedin vervullen?
De belangrijkste functie van een EH is volgens de geïnterviewde het bieden van een tool voor congestiemanagement. EH's kunnen bedrijven ondersteunen die door een gebrek aan transportcapaciteit beperkt worden in hun groei. Het idee is dat een EH bedrijven helpt hun energieverbruik en productieprocessen beter af te stemmen, waardoor ze binnen hun gecontracteerde capaciteit kunnen blijven opereren.
Stedin ziet zichzelf daarbij niet als aanbieder van een kant-en-klaar product, maar eerder als een facilitator die gegevens en ondersteuning biedt. De focus ligt op het aanbieden van datadiensten, berekeningen en contractondersteuning, waarmee bedrijven beter kunnen samenwerken en hun processen kunnen optimaliseren.

3) Wat houdt deelname tegen, en wat kan Stedin over de streep trekken?
Een belangrijk obstakel is het risicomijdende gedrag van stakeholders. Veel onzekerheden rondom EH's maken het lastig om bedrijven te overtuigen van de voordelen. Daarbij speelt het volgende:

- **Onzekerheid over de praktijk:** Het is nog onduidelijk hoe EH's in de praktijk functioneren en hoe bedrijven hun processen aanpassen aan de samenwerking in een hub.
- **Bezwaren van TenneT:** TenneT vreest dat EH's negatieve gevolgen kunnen hebben voor congestiebeheer op distributieniveau. Dit remt de implementatie van grootschalige projecten.
- **Interne uitdagingen bij Stedin:** In vergelijking met andere netbeheerders, zoals Enexis en Alliander, ontbreekt bij Stedin een lange termijnvisie en zijn de beschikbare middelen beperkter. De geïnterviewde ziet dit als een uitdaging, maar benadrukt dat het belangrijk is om juist nu actie te ondernemen.

Conclusie

Energiehubs bieden volgens de geïnterviewde veel potentie om structurele problemen zoals netcongestie op te lossen. Conceptueel wordt de waarde van EH's erkend, maar er zijn nog veel vragen over de praktische toepasbaarheid en het gedrag van bedrijven binnen deze hubs. Kleine pilots worden gezien als een effectieve manier om ervaring op te doen, risico's te begrijpen en te leren hoe bedrijven omgaan met de veranderingen die een EH vereist.
De geïnterviewde maakt zich sterk voor het versnellen van de implementatie van EH's. Hij benadrukt dat het cruciaal is om op kleine schaal te beginnen en stap voor stap te leren van de praktijk. Hiermee kunnen onzekerheden worden weggenomen en kan de waarde van EH's concreter worden aangetoond.
Tegelijkertijd herkent de geïnterviewde de beperkingen van Stedin als assetbeheerder. De focus op het beheren van netwerken, zonder sterke prikkels om te innoveren, kan frustrerend zijn voor medewerkers die een proactievere aanpak willen. Stedin moet daarom werken aan een duidelijkere visie en meer middelen vrijmaken om te investeren in energiehubs.

De geïnterviewde ziet EH's als een noodzakelijke oplossing, maar benadrukt dat er nu actie moet worden ondernomen om verdere congestieproblemen te voorkomen. Het belang van flexibiliteit en samenwerking op kleine schaal wordt hierbij als essentieel beschouwd.

Interview #2: Grid Architect, 10.11.2024.

Achtergrond

X is een gebiedsverantwoordelijke bij een netbeheerder in de provincie Utrecht. Zij is specifiek verantwoordelijk voor de gebieden Stichtse Vecht en Ronde Venen. Haar rol omvat operationeel en toekomstgericht plannen van netinvesteringen, inclusief de functionele omschrijving van projecten en hun impact op het netwerk. Daarnaast werkt zij aan de inzet en ontwikkeling van Energy Hubs (EH's) als onderdeel van strategieën om netcapaciteit te verbeteren en toekomstige leveringszekerheid te waarborgen.

X beschrijving van haar rol benadrukt een dualiteit: enerzijds operationeel gericht (dagelijkse netverzwaring en optimalisatie), anderzijds toekomstgericht (strategische planning en impactanalyse). Dit wijst op een belangrijke balans die netbeheerders moeten vinden tussen huidige operationele uitdagingen en toekomstige flexibiliteitsbehoeften.

Hoofdvragen

1) **Waarom zijn jullie betrokken bij een EH-traject?**

x benadrukt dat de betrokkenheid van de netbeheerder voortkomt uit de noodzaak om leveringszekerheid te garanderen en congestieproblemen op het netwerk te beheersen. Energy Hubs worden gezien als een oplossing om bestaande netcapaciteit efficiënter te benutten en de afhankelijkheid van grootschalige netuitbreiding te verminderen. Hierbij spelen operationele en beleidsmatige afwegingen een rol, waarbij EH's bijdragen aan het balanceren van vraag en aanbod.

2) **Welke taak moet een EH voor jullie vervullen?**

Voor de netbeheerder moeten EH's een bijdrage leveren aan het verbeteren van de flexibiliteit en efficiëntie binnen het energiesysteem. Dit omvat onder meer het gebruik van opslagtechnologieën, vraagsturing, en energie-uitwisseling tussen gebruikers. EH's moeten ook economische groei ondersteunen zonder dat grootschalige investeringen in nieuwe infrastructuur nodig zijn. De technische haalbaarheid en de mate waarin een EH bijdraagt aan de optimalisatie van het netwerk op zowel korte als lange termijn zijn cruciaal.

3) **Wat houdt deelname tegen, en wat kan jullie over de streep trekken?**

Deelname aan EH-trajecten wordt bemoeilijkt door een aantal factoren:

- **Capaciteitsproblemen binnen de organisatie:** Gebiedsverantwoordelijken hebben beperkte tijd en middelen voor het beoordelen van projecten, wat tot vertragingen leidt.
- **Complexiteit van projecten:** Het doorrekenen en plannen van EH-initiatieven vereist een gedetailleerde analyse die vaak tijdrovend is.
- **Verschillende perspectieven:** Gemeenten, bedrijven en netbeheerders hebben vaak uiteenlopende prioriteiten en doelen, wat de samenwerking complex maakt.

Wat deelname aantrekkelijk maakt, is de mogelijkheid om op strategische locaties impactvolle projecten te implementeren, zoals gebieden met hoge lokale opwek en lage consumptie. Door automatisering en standaardisering van projectanalyses kunnen initiatieven sneller en effectiever worden beoordeeld.

Conclusie
Energy Hubs bieden aanzienlijke kansen om congestie te beheersen en de energie-efficiëntie te verbeteren, terwijl ze tegelijkertijd economische groei mogelijk maken. Echter, het succes van EH's hangt af van strategische positionering, duidelijke communicatie tussen betrokken partijen, en voldoende capaciteit en middelen binnen de netbeheerder. XXX benadrukt dat een gezamenlijke visie en een geïntegreerde aanpak nodig zijn om de volledige potentie van EH's te benutten.

Interview #3: Innovation Consultant , 18.11.2024.

Introductie
x werkt als adviseur Innovatie bij Stedin, met een focus op systeemintegratie en de ontwikkeling van Energy Hubs. In het interview geeft hij inzicht in de motivatie en uitdagingen van Stedin bij hun betrokkenheid bij Energy Hubs, evenals de rol die deze hubs spelen in het verbeteren van netcapaciteit en het bevorderen van lokale samenwerking.

Hoofdvragen
1) Waarom is Stedin betrokken bij Energy Hubs?
De primaire motivatie van Stedin om betrokken te zijn bij Energy Hubs ligt in het aanpakken van congestie in het energienet. Er zijn twee hoofdpijlers die hierbij centraal staan:

1. **Uitbreiding van infrastructuur:** Het vergroten van de capaciteit van het net om aan de toenemende vraag te voldoen.
2. **Efficiënter gebruik van bestaande infrastructuur:** Dit wordt bereikt door betere afstemming van lokale energieprofielen, waardoor netwerken slimmer benut kunnen worden.

Energy Hubs worden gezien als een oplossing om lokale samenwerking te stimuleren en tegelijkertijd congestie te verminderen. Door lokale profielen beter op elkaar af te stemmen, kunnen bestaande netten efficiënter gebruikt worden, zonder dat grote infrastructurele uitbreidingen noodzakelijk zijn.

2) Welke taak moet een EH voor Stedin vervullen?
Een Energy Hub heeft zowel een technische als organisatorische taak:

- **Technisch:** Het verbeteren van de gebruiksefficiëntie van de bestaande infrastructuur en het accommoderen van uitbreidingen binnen de huidige capaciteitslimieten.
- **Organisatorisch:** Het creëren van een samenwerkingsverband waarbij Stedin afspraken kan maken met één entiteit (bijvoorbeeld een coöperatie of BV) in plaats van met meerdere individuele partijen. Dit maakt het netbeheer eenvoudiger en verhoogt de kans van slagen van een Energy Hub.

Vroon benadrukt dat het organisatorisch vermogen cruciaal is. Zonder een verbindende entiteit of groepsstructuur komt een Energy Hub niet van de grond. Deze entiteiten kunnen nieuw worden opgericht, zoals bij nieuwbouwwijken, of voortkomen uit bestaande samenwerkingen, bijvoorbeeld binnen bedrijventerreinen.

De rol van Stedin binnen Energy Hubs
Stedin zelf neemt geen leidende rol in de ontwikkeling van Energy Hubs, maar faciliteert en ondersteunt processen door voorlichting te geven over de voorwaarden en het opstarten van samenwerking. De organisatie zorgt voor duidelijkheid over de capaciteitsvoorwaarden en maakt

afspraken met de betrokken entiteiten. Echter, het initiatief en de leiding liggen vaak bij gemeenten of lokale partijen. Stedin ziet zichzelf vooral als leverancier van netcapaciteit en niet als directe deelnemer in een Energy Hub.

Redenen voor ondersteuning en uitdagingen

Stedin ondersteunt Energy Hubs omdat ze bijdragen aan een efficiënter gebruik van netcapaciteit en helpen om piekbelastingen te verminderen. Dit is belangrijk op zowel onderstation niveau als op grotere schaal. Door betere afstemming van energievraag en -aanbod kan de infrastructuur minder snel haar limieten bereiken.

Een uitdaging is echter de afstemming met andere netbeheerders, zoals TenneT. Op bepaalde momenten kan het voorkomen dat een lokale piekbelasting door een Energy Hub samenvalt met een piek elders in het hogere net. Hierin moet samenwerking en afstemming plaatsvinden om dit soort situaties te voorkomen. Stedin onderzoekt bijvoorbeeld manieren om capaciteiten flexibel op dagbasis te benutten in plaats van structureel dynamische profielen te volgen, wat minder praktisch en haalbaar is.

Perspectief van gebruikers en beperkingen

Vroon merkt op dat Energy Hubs voor gebruikers meestal als positief worden ervaren. Ze bieden toegang tot restruimte in het netwerk, waardoor bedrijven kunnen groeien zonder verdere beperkingen op te leggen. Toch kan het implementeren van een Energy Hub uitdagingen met zich meebrengen. Zo moeten er oplossingen komen voor afroepbaar vermogen, zoals batterijen, om pieken en dalen op te vangen. Dit brengt kosten met zich mee en kan mogelijk weerstand oproepen bij betrokken partijen.

Afstemming met TenneT en flexibiliteit

Stedin werkt samen met TenneT om limieten en voorwaarden voor Energy Hubs vast te stellen. Hierin worden bijvoorbeeld afspraken gemaakt over piekbelasting op specifieke momenten en hoe deze kan worden gemitigeerd. Flexibele capaciteitsbenutting, waarbij profielen op dagbasis worden aangepast, wordt gezien als een haalbare en wenselijke oplossing. Het structureel volgen van dynamische profielen wordt minder wenselijk geacht vanwege de complexiteit en de variabiliteit in piekmomenten.

Conclusie

Energy Hubs spelen kunnen een rol spelen in het verbeteren van netcapaciteit en het verminderen van congestie door lokale samenwerking en betere afstemming van profielen. Stedin ziet het als een oplossing die de efficiëntie van bestaande netten vergroot zonder direct te investeren in grootschalige uitbreidingen. Hun rol blijft ondersteunend en faciliterend, waarbij ze de voorwaarden en capaciteitsgrenzen duidelijk stellen. Hoewel er uitdagingen zijn, zoals de afstemming met andere netbeheerders, het benodigde organisatorisch vermogen, en de kosten voor afroepbaar vermogen, biedt het concept van Energy Hubs een veelbelovende oplossing voor de toekomstige energievraag.

Interview #4: EH Researcher & Consultant, 19.11.2024.

Achtergrond

Het gesprek richt zich op het valideren van inzichten uit eerdere interviews over Energy Hubs (EH's) en het delen van ervaringen met bedrijven die bij dergelijke projecten betrokken zijn. De geïnterviewde, die eerder zelf onderzoek deed naar EH's, heeft uitgebreide kennis over de bedrijfsdynamiek rondom EH's en de uitdagingen waarmee bedrijven te maken krijgen.

Hoofdvragen

1. **Hoe wordt eigenaarschap ervaren door bedrijven?**

Inzicht in eigenaarschap: Veel bedrijven hebben een beperkt begrip van wat eigenaarschap in een EH betekent. Het wordt vaak pas een onderwerp wanneer bedrijven direct met energiezekerheidsproblemen worden geconfronteerd. Bedrijven die al betrokken zijn bij EH's hebben doorgaans een beter begrip van eigenaarschap, maar het ontbreekt bij veel andere bedrijven aan basale kennis over netstructuren en hun rol daarin.

Belang van eigenaarschap: Zodra bedrijven bewust worden gemaakt van hun rol en verantwoordelijkheid binnen een EH, groeit het besef van het belang van eigenaarschap.

2. **Wat is de rol van financieel kapitaal?**

Financieel kapitaal: Kostenbesparingen en de mogelijkheid tot terugverdienen (bijvoorbeeld door opslag of handel in energie) worden door bedrijven als belangrijke motivatoren genoemd. Tegelijkertijd zijn veel bedrijven onzeker over investeringen vanwege het ontbreken van solide businessmodellen en duidelijke financiële voordelen. Het idee van gesocialiseerde kosten, waarbij kosten van een EH worden gedeeld als deze voor het systeem voordelig is, wordt besproken als een mogelijke oplossing om bedrijven te overtuigen deel te nemen.

3. **Hoe maken bedrijven beslissingen rondom deelname?**

Energiezekerheid als primaire drijfveer: Bedrijven gaan pas actief op zoek naar EH-oplossingen als zij zelf met problemen zoals congestie worden geconfronteerd. Vaak zijn het bedrijven op bedrijventerreinen die als eerste deelnemen en anderen motiveren om ook in te stappen.

Onzekerheid rondom modellen en regelgeving: Het ontbreken van uitgewerkte modellen en de complexiteit van regelgeving zorgen voor terughoudendheid. Bedrijven zijn vaak huiverig om te investeren in iets waarvan de voordelen nog niet duidelijk zijn.

4. **Wat kan bijdragen aan betere besluitvorming?**

Duidelijke verwachtingen: Inzicht geven in de impact van hun keuzes, zoals het gebruik van opslagcapaciteit of investeringen in flexibiliteit is onvoldoende duidelijk. Door concrete simulaties en businessmodellen te tonen, krijgen bedrijven meer grip op de mogelijke gevolgen van hun investeringen.

Betere communicatie: De geïnterviewde benadrukt het belang van heldere en begrijpelijke communicatie over netstructuren, kosten en voordelen. Dit is essentieel om bedrijven te betrekken bij EH-trajecten.

Aanvullende Inzichten

Complexiteit van EH-besluitvorming:
EH's combineren technische, financiële en organisatorische factoren die elkaar beïnvloeden. Het gedrag van systemen zoals batterijen en de interacties tussen gebruikers vragen om duidelijke afspraken binnen een EH. Het belang van maatwerk per situatie wordt benadrukt.

Data en simulaties als hulpmiddel:
Gestandaardiseerde data en simulatiemodellen bieden waardevolle inzichten, maar blijven afhankelijk van de specifieke situatie. Besluitvorming kan beter worden ondersteund door tools die bedrijven laten zien wat de impact van hun keuzes is op zowel korte als lange termijn.

Samenwerking met netbeheerders:
Netbeheerders spelen een cruciale rol bij het faciliteren van EH's, maar hun belangen zijn niet altijd in lijn met die van bedrijven. Tools en transparantie kunnen helpen om deze belangen beter op elkaar af te stemmen.

Energiezekerheid en capaciteit:
Bedrijven hebben vaak een verkeerd beeld van hoe EH's kunnen bijdragen aan energiezekerheid. Het belang van flexibiliteit en het goed benutten van de capaciteit binnen de netlimieten wordt benadrukt als kernpunt van EH's.

Toekomstige ontwikkeling van EH's:
De geïnterviewde beschouwt EH's als een waardevol instrument voor de energietransitie, maar benadrukt dat de modellen en tools nog in een exploratiefase zitten. Verdere verfijning en bredere acceptatie zijn nodig om de volledige potentie van EH's te benutten.

Interview #5: SME Energy Consultant , 21.11.2024.

Achtergrond
X heeft meer dan 25 jaar ervaring in de energiesector, met een focus op strategie, innovatie, en energietransitie. Hij studeerde elektrotechniek aan de TU Eindhoven en richtte zich al vroeg op hernieuwbare energie en de integratie van zonnepanelen. Zijn loopbaan omvatte onder andere technische en strategische functies bij netbeheerders en commerciële rollen in de kabel- en energiesector. Tegenwoordig werkt hij veel met bedrijven en stakeholders in de markt, met een focus op flexibiliteit en duurzame energieoplossingen.
Tijdens het interview benadrukte x zijn uitgebreide ervaring in de sector en de inzichten die hij heeft opgedaan door te werken met bedrijven en netbeheerders. Hij bekijkt energiehubs zowel vanuit een technisch als een commercieel perspectief, en combineert deze invalshoeken in zijn adviezen.

Hoofdvragen
1) Waarom zijn bedrijven betrokken bij een EH-traject?
Bedrijven kiezen doorgaans voor deelname aan een energiehubtraject omdat ze een specifieke oplossing zoeken voor een probleem met hun energievoorziening, zoals een gebrek aan netcapaciteit of lange wachttijden voor een netaansluiting. Deze groep bedrijven wil vaak snel een oplossing, met

een termijn van enkele jaren of korter. In veel gevallen wordt een energiehub een aantrekkelijke optie omdat het een gezamenlijk gedragen oplossing biedt voor een gedeeld probleem.
Daarnaast zijn er bedrijven die niet direct met een probleem kampen, maar deelnemen vanuit een toekomstgerichte strategie. Deze bedrijven kijken naar hun energiebehoefte op de lange termijn en zien een energiehub als een mogelijkheid om energiekosten te optimaliseren, duurzaamheid te bevorderen, en CO_2-uitstoot te verminderen. Deze groep wordt vooral vertegenwoordigd door grotere bedrijven in de procesindustrie, die vaak investeren in lange-termijnoplossingen met een horizon van vijf jaar of meer.
Soms ontstaat betrokkenheid ook door externe stimulansen, zoals initiatieven van provincies, gemeenten of commerciële partijen. Hierbij wordt de energiehub gepresenteerd als een kans voor economische en duurzame ontwikkeling. x merkt echter op dat de meeste bedrijven pas deelnemen wanneer ze met een direct probleem geconfronteerd worden.

2) Welke taak moet een EH voor bedrijven vervullen?
De belangrijkste taak van een energiehub is het garanderen van energiezekerheid. Bedrijven willen de zekerheid dat ze op elk moment over voldoende energie kunnen beschikken om hun bedrijfsprocessen draaiende te houden. Dit is vooral belangrijk in sectoren waar energie een cruciale rol speelt, zoals de industrie. Naast energiezekerheid moet een energiehub energie kunnen leveren tegen acceptabele kosten, afgestemd op de specifieke behoefte van bedrijven.
Secundair kan een energiehub bijdragen aan verduurzaming en het verlagen van de CO_2-uitstoot. Bedrijven zien dit niet alleen als een maatschappelijke verantwoordelijkheid, maar ook als een manier om hun concurrentiepositie te versterken en aan regelgeving te voldoen. Het aanbieden van flexibiliteit, zoals het inzetten van batterijen of bedrijfsprocessen voor de onbalansmarkt, wordt ook genoemd als een waardevolle toevoeging. Echter, deze aspecten komen meestal pas aan bod nadat het primaire probleem – energiezekerheid – is opgelost.
X benadrukt dat bedrijven verschillend omgaan met betaalbaarheid. Voor sommige bedrijven is energie een groot deel van hun kostenstructuur, terwijl het voor andere bedrijven slechts een marginale post is. Dit bepaalt mede hoe aantrekkelijk een energiehub is voor een bedrijf en welke mate van flexibiliteit of verduurzaming interessant wordt geacht.

3) Wat houdt bedrijven tegen, en wat kan hen over de streep trekken?
Er zijn verschillende redenen waarom bedrijven terughoudend kunnen zijn om deel te nemen aan een energiehub. Een veelvoorkomende reden is dat een bedrijf geen urgent probleem ervaart en energie niet als een kernonderdeel van zijn bedrijfsvoering ziet. Vooral kleinere bedrijven, zoals in het MKB, hebben vaak beperkte middelen en expertise en richten zich voornamelijk op hun kernactiviteiten.
Daarnaast kan concurrentiegevoeligheid een rol spelen. In industriële gebieden zoals de Botlek, waar veel grote bedrijven dicht bij elkaar gevestigd zijn, bestaat soms de angst om gevoelige gegevens over energieverbruik en bedrijfsprocessen te delen. Dit kan deelname aan een gezamenlijke oplossing bemoeilijken.
Ook tijdsdruk kan een belemmering zijn. Het opzetten van een energiehubtraject vereist investeringen in tijd en middelen, iets waar bedrijven met korte-termijndoelstellingen of beperkte capaciteit minder snel toe bereid zijn. Toch worden bedrijven over de streep getrokken wanneer een energiehub een directe oplossing biedt voor een probleem, zoals congestie op het elektriciteitsnet of vertraging bij een netaansluiting. In deze gevallen zien bedrijven deelname vaak als noodzakelijk om hun operationele continuïteit te waarborgen.

Een andere belangrijke stimulans is het vooruitzicht van een gezonde businesscase. Bedrijven zijn eerder geneigd deel te nemen wanneer duidelijk wordt dat de kosten opwegen tegen de baten, en wanneer de energiehub bijdraagt aan kostenreductie of procesoptimalisatie.

Conclusie
Energiehubs bieden bedrijven een waardevolle oplossing voor problemen zoals netcongestie en energietransitie. De belangrijkste motivatie voor deelname is energiezekerheid, maar bedrijven zien ook secundaire voordelen in verduurzaming en flexibiliteit. Tegelijkertijd bestaan er drempels, zoals tijdsdruk, concurrentiegevoeligheid en een gebrek aan urgentie.
Toekomstgericht denken en het opnemen van energievraagstukken in strategische bedrijfsplannen kunnen veel problemen voorkomen. Echter, niet alle bedrijven hebben de middelen of expertise om dit proactief aan te pakken. Hier ligt een belangrijke rol voor netbeheerders en overheden om bedrijven te ondersteunen en duidelijke kaders te bieden.
Energiehubs hebben de potentie om een sleutelrol te spelen in de energietransitie, maar succes hangt af van samenwerking, heldere regelgeving, en het vermogen van bedrijven om hun problemen en doelen in een bredere context te plaatsen.

Interview #6: Expert Hubs & Innovation, 22.11.2024.

Achtergrond
X is werkzaam bij Stedin, op de afdeling Innovatie in Rotterdam. Binnen de subafdeling Flexibiliteit en Systeemintegratie werkt hij aan oplossingen voor netcongestie en optimalisatie van het elektriciteitsnet. Hij is betrokken bij diverse projecten, waaronder twee pilots voor energiehubs (EH's) in Zeeland en Utrecht, en andere initiatieven zoals waterstofonderzoek en flexibel laden. Vanuit zijn rol combineert hij technische expertise met strategisch inzicht in hoe bedrijven en netbeheerders samenwerken om de energietransitie te faciliteren.

Hoofdvragen
1) Waarom zijn jullie betrokken bij een EH-traject?
Stedin is betrokken bij EH-trajecten om de uitdagingen van netcongestie te adresseren. De congestie op het elektriciteitsnet belemmert bedrijven om te elektrificeren of te groeien. Vanuit de afdeling Innovatie onderzoekt Stedin hoe bedrijven ondanks capaciteitsproblemen kunnen verduurzamen of uitbreiden. EH's bieden een potentiële oplossing door flexibele energieverdeling en samenwerking tussen bedrijven mogelijk te maken, wat in sommige gevallen netwerkverzwaring kan uitstellen of verminderen.
Daarnaast speelt de betrokkenheid van bedrijven een grote rol. Enthousiasme en bereidheid vanuit bedrijven om te investeren en samen te werken zijn belangrijke voorwaarden voor het starten van een EH-traject. De vraag vanuit bedrijven zelf, gecombineerd met de mogelijke structurele voordelen voor het elektriciteitsnet, zijn de belangrijkste drijfveren voor Stedin.

2) Welke taak moet een EH voor jullie vervullen?
De primaire taak van een EH is het ontlasten van het elektriciteitsnet door het verbeteren van de flexibiliteit in energiegebruik en -opslag. Voor Stedin is dit essentieel, omdat het helpt om de druk op het net te verminderen en tegelijkertijd bedrijven te ondersteunen in hun energiebehoeften. EH's moeten niet alleen tijdelijke oplossingen bieden, maar bij voorkeur een blijvende impact hebben door bedrijven te helpen verduurzamen en efficiënter met energie om te gaan.

Daarnaast moeten EH's bedrijven perspectief bieden. Zelfs in situaties van netcongestie kunnen EH's bijdragen aan groei en verduurzaming. Structurele oplossingen zoals de integratie van batterijen en zonne-energie kunnen bedrijven meer autonomie geven. Voor Stedin is het ideaal dat EH's ook een langetermijnoplossing vormen, zodat de geïnvesteerde middelen en tijd niet verloren gaan.

3) Wat houdt deelname tegen, en wat kan jullie over de streep trekken?
Een belangrijke barrière voor EH's is de complexiteit van het opzetten en implementeren ervan. Het coördineren van bedrijven, aanpassen van processen, en het opstellen van contracten en technische afspraken kost tijd en moeite. Dit kan bedrijven ontmoedigen, vooral als een EH slechts als tijdelijke oplossing wordt gezien. Als de businesscase niet duidelijk genoeg is, kunnen bedrijven aarzelen om te investeren.
Voor Stedin zelf spelen enkele technische en organisatorische uitdagingen een rol. Bijvoorbeeld: een EH kan impact hebben op netbalancering en samenwerking met andere partijen zoals TenneT. Ook juridische kwesties, zoals aansprakelijkheid, en praktische problemen, zoals het implementeren van flexibiliteitsmechanismen, kunnen barrières vormen. Het succes van een EH hangt mede af van de bereidheid van alle betrokken partijen om samen te werken en innovatieve oplossingen te ondersteunen.
Wat bedrijven over de streep kan trekken, is een heldere en overtuigende businesscase die zowel op korte als lange termijn waarde biedt. Enthousiasme van bedrijven en duidelijke voordelen, zoals kostenbesparingen en duurzame groei, zijn cruciaal om bedrijven te motiveren. Voor Stedin zijn de structurele voordelen voor het elektriciteitsnet en de verduurzaming van de regio de belangrijkste factoren om verder te investeren in EH's.

Conclusie
Energiehubs bieden een waardevolle oplossing voor de uitdagingen van netcongestie en energietransitie. Ze helpen bedrijven verduurzamen, groeien en flexibeler omgaan met hun energiegebruik. Voor Stedin zijn EH's een kans om de druk op het net te verlichten en duurzame energieoplossingen te ondersteunen.
Echter, de implementatie van EH's kent uitdagingen. Bedrijven zien EH's soms als een tijdelijke oplossing, terwijl Stedin streeft naar structurele en langdurige impact. Technische en organisatorische obstakels, zoals netbalancering en juridische kwesties, kunnen deelname belemmeren. Toch blijft het enthousiasme van bedrijven en de duidelijke voordelen voor zowel bedrijven als het elektriciteitsnet de belangrijkste motivators.
In de toekomst kunnen EH's een structureel onderdeel worden van Stedin's strategie, vooral als ze effectief bijdragen aan flexibiliteit en verduurzaming. Echter, hun succes hangt af van samenwerking tussen bedrijven, netbeheerders en overheden. Een heldere visie, standaardisatie, en coördinatie zijn nodig om EH's schaalbaar en efficiënt te maken.

Interview #7: Transition Manager Energy Systems, 26.11.2024.

Achtergrond
X is transitiemanager bij de afdeling Asset Management van Stedin. Hij werkt vanuit het team Transitieplanning, dat zich richt op de middellange- en langetermijnontwikkelingen in Zuid-Holland. Hij coördineert samen met overheden en andere stakeholders de noodzakelijke investeringen in het energienetwerk. X heeft specifieke ervaring met de regionale infrastructuurplanning en de integratie van oplossingen zoals energiehubs (EH’s) in stedelijke en provinciale beleidsagenda's.

Hoofdvragen

1) Waarom zijn jullie betrokken bij een EH-traject?

Stedin's betrokkenheid bij EH-trajecten komt voort uit de behoefte om congestieproblemen op het elektriciteitsnet te adresseren en om netcapaciteit efficiënter te benutten. Via regionale infrastructuurprogramma's, zoals het meerjarenplan infrastructuur, energie en klimaat (MIEK) in Zuid-Holland, werken zij samen met gemeenten en provincies aan oplossingen. EH's komen hier steeds vaker naar voren als een potentieel instrument voor het beter benutten van bestaande infrastructuur en het voorkomen van netverzwaring.

Gemeenten zien EH's vaak als een middel om congestie te voorkomen en lokale energie beter te benutten. Voor Stedin ligt de toegevoegde waarde meer in het faciliteren van groeiende vraag naar netcapaciteit als gevolg van (economische) groei of verduurzaming door efficiëntere benutting van de bestaande infrastructuur. Hierdoor kan de afhankelijkheid van tijdintensieve grootschalige investeringen in nieuwe infrastructuur in potentie verminderd worden. Dit verschil in prioriteiten benadrukt de complexe rol van EH's als zowel tijdelijke als structurele oplossing.

2) Welke taak moet een EH voor jullie vervullen?

EH's moeten voor Stedin bijdragen aan het beter benutten van bestaande netcapaciteit. Dit omvat het balanceren van vraag en aanbod tussen bedrijven, zodat investeringen in netverzwaringen kunnen worden uitgesteld of voorkomen. Daarnaast moeten EH's flexibiliteit in het systeem bevorderen door bijvoorbeeld gebruik te maken van opslagtechnologieën en energie-uitwisseling tussen bedrijven.

Een bijkomende taak van EH's is het ondersteunen van economische groei van bedrijven binnen de beperkingen van het bestaande netwerk. Gemeenten zien EH's vaak als een manier om congestie op lokaal niveau te beheersen en bedrijven meer autonomie te geven in hun energiebeheer. Echter, volgens x is het cruciaal dat EH's technisch haalbaar zijn en effectief bijdragen aan de optimalisatie van het netwerk, zowel op korte als lange termijn.

3) Wat houdt deelname tegen, en wat kan jullie over de streep trekken?

Deelname aan EH's wordt bemoeilijkt door enkele factoren:

- **Beperkte capaciteit binnen Stedin**: Gebiedsverantwoordelijken, die essentieel zijn voor het beoordelen van de impact van EH's op het netwerk, zijn al overbelast met lopende projecten. Dit gebrek aan capaciteit vormt een bottleneck voor verdere betrokkenheid.
- **Complexiteit van initiatieven**: Het doorrekenen van individuele projecten en het ontwikkelen van oplossingen kost veel tijd en middelen. Veel initiatieven missen duidelijke economische of technische voordelen, wat kan leiden tot een inefficiënte inzet van middelen.
- **Verschillen in perspectief**: Gemeenten zien EH's als een manier om lokale problemen op te lossen, bedrijven zien EH's vaak als noodoplossing of als een verdienmodel, terwijl Stedin kijkt naar het grotere systeem en langetermijnvoordelen. Dit verschil in visie kan tot frictie leiden.

Op dit moment worden EH vooral geïnitieerd op lokaal niveau doordat bedrijven samen willen werken op het gebied van energie. Door de beperkte schaal van de intiatieven, zijn het er in aantal potentieel veel, terwijl de impact (bijvoorbeeld het voorkomen van congestie of investeringen) minimaal is. Tegelijkertijd zorgt een aanvraag voor een EH aan de kant van Stedin wel de nodige investeringen in tijd en budget.

Wat deelname aantrekkelijk maakt voor Stedin, is de mogelijkheid om EH's strategisch te positioneren op locaties waar ze een duidelijke meerwaarde bieden. X noemt als voorbeeld gebieden waar veel energie wordt opgewekt, maar weinig wordt verbruikt. Door gebruikers naar deze locaties te verplaatsen, kunnen transportkosten en netverzwaringen worden verminderd. Het identificeren van deze locaties is een taak van Stedin en dat wordt nu geïnitieerd. Daarnaast ziet hij mogelijkheden in het verder automatiseren van de berekening van netimpact, zodat initiatieven sneller kunnen worden beoordeeld.

Conclusie

Energiehubs hebben een groot potentieel om de energietransitie te ondersteunen door netcapaciteit efficiënter te benutten en bedrijven meer flexibiliteit te bieden. Voor Stedin liggen de belangrijkste voordelen in het balanceren van vraag en aanbod, het beperken van investeringen in nieuwe infrastructuur, en het ondersteunen van groeiende vraag naar netcapaciteit binnen de beperkingen van het netwerk.

Toch zijn er aanzienlijke uitdagingen. Het verschil in perspectief tussen gemeenten, bedrijven en netbeheerders benadrukt de noodzaak van duidelijke communicatie en gezamenlijke planning. Bedrijven lijken vanuit het eindeplaatje van een EH te redeneren, waar deze al volledig functioneel is, terwijl er onvoldoende rekening wordt gehouden met het lange aanlooptraject. Ook zal een cultuuromslag noodzakelijk zijn, onbeperkt groeien in netcapaciteit zal geen vanzelfsprekendheid meer zijn. Vervolgens zal de manier waarop bedrijven batterijen in willen zetten waarschijnlijk niet aansluiten bij de behoefte van de netbeheerder.

Gemeenten zien EH's vaak als een oplossing voor lokale problemen, terwijl Stedin meer focus legt op het systeem als geheel en langetermijnoplossingen. Een betere afstemming van rollen en verwachtingen is noodzakelijk om het potentieel van EH's volledig te benutten. Een voorbeeld hiervan is dat externe partijen niet noodzakelijkerwijs op dezelfde manier het net doorrekenen, met andere zienwijzen van de EH tot gevolg.

X benadrukt dat het succes van EH's ook afhankelijk is van de juiste balans tussen huidige investeringen en toekomstige voordelen. Hoewel EH's aanzienlijke investeringen vragen van de bedrijven zelf, kunnen ze bijdragen aan het voorkomen van grootschalige netverzwaringen. Dit maakt ze een waardevolle optie voor Stedin, mits ze strategisch worden ingezet en ondersteund door voldoende capaciteit en middelen.

Een positief effect van EH's is dat bedrijven en gemeenten zich steeds meer bewust worden dat energie een schaars goed is en dat de beschikbaarheid van ervan niet langer een vanzelfsprekendheid is. Deze bewustwording is een belangrijke voorwaarde voor het succes van de energietransitie.

Interview #8: Consultant Energy System SmartGrids , 28.11.2024.

Achtergrond

X is consultant energiesystemen bij EQUANS Nederland, een technische dienstverlener gespecialiseerd in ontwerp, realisatie, beheer en onderhoud van grote technische installaties. EQUANS richt zich voornamelijk op industrie, ziekenhuizen en grote bedrijven zoals ASML. X heeft een achtergrond in energieprocestechnologie en bedrijfskunde, en heeft eerder gewerkt als accountmanager en gebiedsregisseur bij Stedin. Bij EQUANS is zijn expertise gericht op netcongestie en smart grids, waarbij hij klanten helpt omgaan met beperkte netcapaciteit en verduurzamingsopgaven.

Hoofdvragen

1) **Waarom zijn jullie betrokken bij een EH-traject?**

EQUANS ondersteunt bedrijven die te maken hebben met netcongestie en helpt hen slim om te gaan met de beschikbare capaciteit. Energy Hubs worden door EQUANS gezien als een oplossing om samenwerking tussen bedrijven te bevorderen en capaciteit efficiënter te benutten. De focus ligt op slimme contractvormen en technische oplossingen, zoals directe lijnen en cable pooling, om klanten te ondersteunen bij hun verduurzamingsopgaven zonder dat zij direct afhankelijk zijn van netverzwaring.

2) Welke taak moet een EH voor jullie vervullen?

Een Energy Hub moet bijdragen aan het optimaliseren van de beschikbare netcapaciteit door samenwerking en flexibiliteit te stimuleren. Dit kan onder andere via gedeelde opslag, het slim benutten van energiepieken en het creëren van kostenvoordelen voor deelnemers. Daarnaast biedt een EH-kansen voor bedrijven om hun verduurzaming te versnellen en hun operationele kosten te verlagen. Voor EQUANS speelt de hub ook een rol in het creëren van bewustzijn bij bedrijven over hun flexibiliteitsmogelijkheden, aangezien veel klanten vaak niet beseffen hoeveel potentieel ze hebben om bij te dragen aan een beter gebruik van het net.

3) Wat houdt deelname tegen, en wat kan jullie over de streep trekken?

Deelname aan EH's wordt belemmerd door:
- **Gebrek aan motivatie en vertrouwen:** Bedrijven die voldoende capaciteit hebben, zien vaak geen directe voordelen in deelname en blijven vasthouden aan traditionele werkwijzen.
- **Technische en contractuele barrières:** Het huidige beleid, zoals het bepalen van groepscapaciteit op basis van de hoogste piek, ontmoedigt samenwerking tussen bedrijven.
- **Gebrek aan kennis:** Veel bedrijven hebben onvoldoende inzicht in hun energiegebruik en flexibiliteitsopties, wat hen terughoudend maakt om te participeren.

Wat deelname aantrekkelijk maakt, zijn concrete voordelen zoals lagere kosten, verbeterde capaciteit en een duidelijke meerwaarde voor het bedrijventerrein als geheel. EQUANS pleit ook voor meer flexibiliteit en transparantie in de samenwerking met netbeheerders.

Aanvullende Inzichten

De definitie van netcongestie

X geeft een praktische definitie van netcongestie vanuit het perspectief van EQUANS: het onvermogen van klanten om extra capaciteit te verkrijgen voor verduurzamingsplannen, zoals elektrificatie van transport of productieprocessen. Hij benadrukt dat netcongestie niet alleen een technische uitdaging is, maar ook directe economische implicaties heeft voor bedrijven.

Langetermijnplanning versus ad-hocoplossingen

De geïnterviewde legt uit dat EQUANS probeert klanten zowel kortetermijnoplossingen als langetermijnstrategieën te bieden. Hoewel klanten vaak pas bij EQUANS aankloppen als het probleem urgent wordt (zoals een brief van de netbeheerder over capaciteitsoverschrijding), werkt EQUANS aan modulaire oplossingen die met de klant mee kunnen groeien, zoals gefaseerde laadinfra of batterijcapaciteit.

De rol van gemeenten en provincies

De geïnterviewde benadrukt dat overheden vaak een belangrijke, maar wisselende rol spelen. Sommige gemeenten en provincies nemen een proactieve houding aan bij het ontwikkelen van

Energy Hubs, terwijl anderen volledig afwezig zijn. Hij ziet echter een risico in initiatieven waarbij bedrijven zonder intrinsieke motivatie worden gedwongen samen te werken, wat vaak tot mislukking leidt. Dit benadrukt het belang van een gedegen probleemanalyse en bestaande samenwerkingsstructuren.

Hindernissen door regelgeving en contractuele beperkingen
De huidige regelgeving, zoals de bepaling van groepscapaciteit op basis van de hoogste piek, ontmoedigd bedrijven om aan een Energy Hub deel te nemen. Dit versterkt individuele optimalisatie, wat contraproductief is voor het collectieve doel van flexibiliteit en samenwerking.

De rol van netbeheerders
Hij wijst op een gebrek aan duidelijke communicatie tussen netbeheerders en bedrijven, vooral voor middelgrote klanten. Er zijn kansen in rollen zoals de "flex hunters" die actief naar flexibele oplossingen zoeken. Hij pleit voor meer transparantie en samenwerking, vooral tussen regionale netbeheerders en TenneT, om Energy Hubs beter te ondersteunen.

Gedragsverandering en bewustwording bij bedrijven
Bedrijven zijn vaak sceptisch zijn over het aanpassen van hun energiegedrag, maar dat netcongestie hen dwingt slimmer om te gaan met beschikbare capaciteit. Dit wordt gezien als een eye-opener voor bedrijven, maar vereist intensieve begeleiding en een duidelijke businesscase. Hij benadrukt dat installateurs hierin een cruciale rol kunnen spelen door bedrijven te helpen de waarde van flexibiliteit te ontdekken.

Het spanningsveld tussen collectieve en individuele voordelen
Een fundamenteel probleem: bedrijven denken vaak vanuit hun eigen gewin, terwijl het succes van een Energy Hub afhankelijk is van samenwerking. Hij noemt concrete voorbeelden waarin bedrijven met voldoende capaciteit zich terugtrekken, wat de ontwikkeling van een collectieve oplossing bemoeilijkt.

Wenselijke resultaten van een Energy Hub
Een succesvol resultaat zou een bedrijventerrein zijn waar alle bedrijven deelnemen aan een groepscapaciteitscontract, met slimme benutting van bestaande capaciteit. Dit zou niet alleen economische voordelen bieden, maar ook bijdragen aan een efficiënter gebruik van het netwerk en verduurzaming van bedrijventerreinen.

De bredere rol van Energy Hubs in de energietransitie
Energy Hubs kunnnen een krachtig instrument voor de energietransitie, maar de huidige aanpak vaak schiet vaak tekort. Hij pleit voor een gezamenlijke aanpak waarbij bedrijven, netbeheerders en overheden verantwoordelijkheid nemen voor het ontwerpen en implementeren van hubs die echt waarde toevoegen.

Conclusie
Energy Hubs bieden een krachtige manier om netcongestie aan te pakken en samenwerking tussen bedrijven te stimuleren. Ze kunnen bedrijven helpen slimmer om te gaan met energie en verduurzamingsdoelen te behalen. Echter, succes vereist een sterke intrinsieke motivatie van bedrijven, duidelijke contractuele afspraken en samenwerking met netbeheerders. EQUANS ziet het als hun rol om klanten te begeleiden bij het identificeren van flexibiliteitsmogelijkheden en het

benutten van de voordelen van een EH. X benadrukt dat een cultuurverandering nodig is binnen bedrijven, installateurs en netbeheerders om Energy Hubs succesvol te implementeren en optimaal gebruik te maken van de beschikbare capaciteit.

Interview #9: Senior Consultant Strategic Exploration and Innovation, 02.12.2025.

Achtergrond

De geïnterviewde werkt bij Alliander binnen de afdeling Strategische Verkenningen en Innovatie. Het werk richt zich op het ontwikkelen van regulatoire, organisatorische en technische oplossingen voor uitdagingen zoals netcongestie en Energy Hubs. Dit omvat samenwerking met andere netbeheerders (zoals TenneT, Stedin, Enexis) en private partijen om nieuwe concepten zoals groepscontracten en alternatieve transportovereenkomsten mogelijk te maken. Daarnaast is er betrokkenheid bij nationale innovatieprojecten en de coördinatie tussen verschillende netbeheerders, met een focus op uniforme aanpakken en standaarden binnen de sector.

Hoofdvragen

1) Waarom betrokken bij een EH-traject?

Alliander is betrokken bij Energy Hubs (EH's) als oplossing voor netcongestie en om de beschikbare capaciteit efficiënter te benutten. EH's worden gezien als een manier om groepen gebruikers gezamenlijk afspraken te laten maken over transportcapaciteit en energiegebruik, waardoor netbeheer effectiever kan worden uitgevoerd. De motivatie is zowel technisch (beheersing van het net) als maatschappelijk (bijdragen aan de energietransitie en economische ontwikkeling). Naast het faciliteren van bestaande netten, experimenteert Alliander ook met innovaties zoals open-source platforms voor capaciteits- en energiemanagement om marktpartijen te ondersteunen.

2) Welke taak moet een EH vervullen?

Voor de netbeheerder is de primaire taak van een EH het mogelijk maken van transportcapaciteit binnen een vastgestelde limiet, vooral in congestiegebieden. Daarnaast biedt Alliander ondernemers een handelingsperspectief: inzicht in wat mogelijk is en afspraken die duidelijkheid en zekerheid bieden. EH's kunnen ook bijdragen aan bredere doelen, zoals het stimuleren van flexibiliteit in energiemarkten en het verbeteren van samenwerking tussen bedrijven op bedrijventerreinen. Voor bedrijven biedt een EH zowel kortetermijnoplossingen voor congestie als langetermijnvoordelen door efficiënter gebruik van beschikbare capaciteit.

3) Wat houdt deelname tegen, en wat kan over de streep trekken?

Hindernissen voor deelname zijn onder meer:

- **Onzekerheid bij bedrijven:** Bedrijven missen vaak handelingsperspectief en duidelijke voordelen van deelname.
- **Ongelijke belangen:** Sommige bedrijven hebben voldoende capaciteit en zien weinig reden om bij te dragen aan een gezamenlijke oplossing.

- **Complexiteit van implementatie:** De organisatie en regulering van groepscontracten vereisen maatwerk en gedetailleerde afspraken.

Wat deelname aantrekkelijker maakt, is een helder en transparant proces waarbij ondernemers vertrouwen hebben in de uitkomsten. Innovatieve rollen, zoals de ‘orchestrator’, worden ingezet om bedrijven beter te begeleiden in deze trajecten. Dit maatwerk is essentieel om obstakels weg te nemen en bedrijven over de streep te trekken.

Aanvullende Inzichten

Brede definitie van EH’s:

De geïnterviewde ziet een EH niet als een puur technisch concept, maar als een organisatorische structuur waarin bedrijven samenwerken aan gezamenlijke energiedoelen. Naast elektriciteit kunnen EH’s ook multi-commodity systemen omvatten, zoals warmte en gas. Dit benadrukt de veelzijdigheid van EH’s als middel om verschillende energievraagstukken aan te pakken.

Groepscontracten en regulering:

Alliander ontwikkelt groepscontracten, zoals de Collectieve Capaciteitsbeperkd Contract (C-CBC) voor congestiebeheer en de Groepstransportovereenkomst - een Alternatieve Transport Overeenkomst (ATO) voor bredere toepassingen. Deze contracten worden afgestemd op zowel lokale als landelijke netbeheerders, maar er blijft spanning tussen optimalisatie op distributieniveau en de impact op het bovenliggende TenneT-net.

Rol van netbeheerders in innovatie:

Alliander neemt een voortrekkersrol in de ontwikkeling van software en platforms om EH’s te ondersteunen, soms zelfs buiten de traditionele taken van een netbeheerder. Dit wordt gedaan om de markt op gang te helpen, met de intentie dat private partijen deze taken in de toekomst overnemen.

Spanning tussen lokale en landelijke netoptimalisatie:

Optimalisaties op distributieniveau (bijvoorbeeld binnen een EH) kunnen conflicteren met de belangen van TenneT, dat problemen signaleert bij integratie van lokale flexibiliteit in het landelijke systeem. Deze spanning vraagt om betere coördinatie en afstemming tussen netniveaus.

Maatwerk als sleutel tot succes:

De geïnterviewde benadrukt dat elk EH-project maatwerk vereist. Algemeenheden over archetypes van deelnemers werken niet in de praktijk, omdat elk bedrijventerrein unieke uitdagingen en mogelijkheden heeft. Rollen zoals de ‘orchestrator’ zijn cruciaal om dit maatwerk te faciliteren.

Impact op energiemarkten:

EH’s hebben de potentie om markten te beïnvloeden, zoals de onbalansmarkt en peer-to-peer energiehandel. Nieuwe platforms en regels zijn nodig om de interactie tussen energiemarkten en capaciteitsbeheer effectief te maken zonder conflicten te veroorzaken.

Tijdelijke versus structurele oplossingen:

EH’s worden nu vooral gepositioneerd als oplossingen voor acute congestieproblemen. De geïnterviewde ziet echter ook een bredere rol voor EH’s in een toekomstig energiesysteem, waar continuïteit van bedrijfsvoering en flexibiliteit belangrijker worden dan kostenbesparingen op transporttarieven.

Interview #10 Area Manager DSO, 05.12.2025.

1. Wie ben jij? Wat doe jij?
2. Hoe pak jij congestieproblemen aan?
    a. Kan jij mij een voorbeeld geven van het klantproces.
    b. Wat is jouw doel in dit proces, hoe bepaal je dit doel?
    c. Hou je hier nu rekening mee in je beslissingen? -> kaart.

3. Ben jij bezig met het “nieuwe” energiesysteem?
4. Wat versta jij onder een EH?
5. Wat denk jij dat anderen onder een EH verstaan?
6. Hoe kijk jij naar flexibiliteit op het net?

Huidige aanname:
Netbeheerders voelen een plicht om te participeren bij EH zodat dit perspectief aan bedrijven kan bieden in het geval van congestie. Ook spelen netbeheerders met de alternatieve opgaven die EH’s voor hen kunnen oplossen. Wat dit precies is moet nog blijken, en daar zit, vanuit het risicomijdende gedrag van de operator, een grote nadruk op eventuele “beren op de weg”. De erg technische en complexe aard van dit vraagstuk maakt het ook lastig en tijdsintensief om capaciteitsafnemers bij te staan in het EH-proces, zeker wanneer het onduidelijk is wat de baten voor het net zijn. Inmiddels lijkt het op tso niveau een steeds aantrekkelijkere en belangrijker element van het nieuwe energiesysteem, als je op de visie van Enexis en Alliander af kan gaan.

Transcript interview

Interviewer: Kun je jezelf voorstellen en uitleggen wat je doet?
(X): Ik ben verantwoordelijk voor de capaciteit van het elektriciteitsnet in Delft, Zoetermeer en Rotterdam-Oost. Mijn rol is het juist plannen van netinvesteringen waarbij ik een schakel ben tussen enerzijds klantvragen en anderzijds de uitvoerende keten van onze organisatie. Netcapaciteitsprognoses worden gemaakt met bijvoorbeeld capaciteitsprognoses voor kleinverbruik en grote aansluitaanvragen. Ik schrijf functionele ontwerpen om netuitbreidingen in opdracht gegeven zodat verwachte knelpunten worden voorkomen.

INTERVIEWER: Hoe verloopt het proces vanaf een klantaanvraag tot uitvoering?
X: Klantaanvragen komen binnen via **mijnaansluiting.nl**. Aanvragen onder de 1,75 MVA worden standaard behandeld en gaan direct door naar de technische teams binnen keten ZP. Voor grotere aanvragen (>1,75 MVA) schakelen we key accountmanagers in. Zij beoordelen de aanvraag en ik (GV) doe een technische toets op haalbaarheid binnen het net.
Vervolgens toetsen we of de gevraagde capaciteit overeenkomt met de verwachte behoefte. Indien dat niet het geval is, adviseren we om de aanvraag te herzien, vaak naar beneden. Wanneer een aansluiting onrealistisch duur of technisch complex blijkt, geven we alternatieve opties of kostenindicaties.

Bij grotere aansluitingen, boven de 10 MVA, adviseren we vaak een toekomstbestendige aansluiting. Dit voorkomt dat klanten over enkele jaren opnieuw aanpassingen nodig hebben, wat uiteindelijk duurder en inefficiënt is.

INTERVIEWER: Waarom zijn capaciteitsvragen soms onjuist?
X: Klanten vragen regelmatig te grote aansluitingen aan. Bijvoorbeeld een hotel dat 10 MVA aanvraagt, terwijl onze data laat zien dat vergelijkbare hotels vaak minder nodig hebben. Dit komt soms door een gebrek aan kennis of door conservatieve inschattingen.
Daarnaast zien we bij grote aanvragen (zoals laadpalen) dat men vaak geen rekening houdt met gelijktijdigheidsfactoren. Niet alle laadpalen zullen bijvoorbeeld tegelijk maximaal worden gebruikt, wat betekent dat de gevraagde capaciteit vaak te hoog is.

INTERVIEWER: Wat gebeurt er als een aanvraag onrealistisch is?
X: In zulke gevallen proberen we klanten te adviseren. Voor kleine klanten kijken we of de gevraagde capaciteit verlaagd kan worden. Soms schrikken ze van de kosten en kiezen ze automatisch een kleinere optie. Bij grotere aansluitingen (>10 MVA) adviseren we juist om iets over te dimensioneren. Bijvoorbeeld, als een klant 12 MVA vraagt, raden we aan om naar 15 of zelfs 20 MVA te gaan, omdat het type kabels en componenten dan nauwelijks verschilt in kosten, maar de aansluiting veel toekomstbestendiger is.

INTERVIEWER: Welke factoren spelen mee in het besluitproces?
X: We kijken naar technische haalbaarheid, investeringskosten, maatschappelijke impact. Voor grote projecten kijken we ook naar stikstofuitstoot en ruimtelijke ordening. Dit zijn echter onderwerpen die vaak bij de klant zelf liggen.
Daarnaast houden we rekening met strategische investeringen in het net. Als een gebied veel groei verwacht, bijvoorbeeld door woningbouw of bedrijven, zoeken we koppelkansen om ervoor te zorgen dat het net voorbereid is op toekomstige vermogensvraag.

INTERVIEWER: Hoe verschillen de belangen van stakeholders?
X: Gemeenten en overheden hechten meer belang aan duurzaamheid en maatschappelijke kosten. Netbeheerders balanceren tussen financiële haalbaarheid en bredere maatschappelijke belangen. Klanten kijken vooral naar hun eigen kosten en mogelijkheden, wat soms tot een mismatch leidt in de capaciteitseis.

INTERVIEWER: Wat is de rol van adviseurs in dit proces?
X: Klanten met adviseurs zijn vaak beter voorbereid en doen meer onderbouwde aanvragen. Maar ook daar zien we dat adviseurs soms te conservatief rekenen of onvoldoende rekening houden met gelijktijdigheidsfactoren. Bij twijfel gaan we in gesprek om uitgangspunten te bespreken en tot een efficiënte oplossing te komen.

Interview #11: Energy System Strategy Expert, 07.01.2025.
Key Evaluation Points:

1. **Irrelevant Factors:** The initial evaluation dismisses some aspects, such as total CO2 emissions and other greenhouse gases, because the focus is on the *end state* rather than optimization during implementation. Similarly, effects like biodiversity, air, soil, and water

quality are deemed irrelevant due to existing legal constraints, which make these non-decision variables.
2. **Relevant Factors:** Material scarcity, specifically for chemical energy storage, is relevant due to its impact on end-state operations. Similarly, land use and underground space are important, especially in relation to scarce materials and the supply chain.
3. **Energy Access:** Energy availability is not just about grid capacity but also the spatial requirements for batteries and other infrastructure. This includes municipal roles in integrating energy storage or conversion equipment.
4. **Manpower and Resources:** There is a debate about the labor and expertise required for traditional grid expansion versus (the running of) energy hubs.
5. **Economic Considerations:** Total societal costs (TOTEX) are more relevant than merely capital or operational expenditures. Annualizing costs over the system's lifespan ensures a balanced view.
6. **Systemic Effects:** The interplay between low and high-voltage networks, as well as radial versus meshed systems, is emphasized. Parallel flows, congestion, and broader system effects should be captured in evaluations.
7. **Subsidies:** Subsidies are not considered in the evaluation since they are policy tools for balancing societal versus financial business cases and are not the focus of the study.
8. **Reliability and Delivery Security:** Security of energy delivery is critical and ties back to grid capacity and energy availability. Reliability, however, is assumed to be sufficient based on precedent.

Summary of Factors to Consider

- **Material Scarcity:** Importance of materials for chemical energy storage.
- **Land Use:** Spatial considerations for infrastructure, including supply chain impacts.
- **Energy Access:** Ensuring energy availability and grid flexibility.
- **Total Societal Costs (TOTEX):** Annualized costs covering the full lifecycle.
- **System Effects:** Interaction between different grid layers and congestion management.
- **Delivery Security:** Guaranteed access and availability of energy.

Factors Omitted and Why

- **CO2 and Other Emissions:** Already regulated and not decision variables.
- **Environmental Impacts (Biodiversity, Water, Soil):** Covered by legal constraints, making them non-influential in design choices.
- **Reliability:** Assumed to be adequate based on historical evidence.
- **Subsidies:** Not relevant as they are external policy tools, not part of direct evaluation criteria.

Interview #12: Manager Legal Affairs, 16.01.2025.

Achtergrond

X heeft sinds 2006 brede ervaring binnen de energiesector. Als jurist, gespecialiseerd in energierecht en regulering, heeft hij vanuit diverse functies inzicht gekregen in zowel de technische als bestuurlijke dimensies van de sector. Hij heeft gewerkt aan asset management en strategische energieplanning. Momenteel is hij werkzaam bij Stedin en betrokken bij de academische werkplaats Klimaat en Energie aan de Universiteit van Tilburg. Zijn focus ligt op sociale innovatie, governance, en regelgeving die rechtvaardige toegang tot energie faciliteert. Het spanningsveld tussen korte- en langetermijnplanning in de sector wordt benadrukt. Hij wijst op de neiging om vooral reactief te handelen op acute capaciteitsproblemen, terwijl strategische planning op de lange termijn vaak onvoldoende wordt geïntegreerd. Zijn expertise ligt in het verbinden van juridische kaders met de bredere maatschappelijke opgaven van de energietransitie.

Hoofdvraag 1: Waarom is Stedin betrokken bij Energy Hubs?
X geeft aan dat Stedin een centrale rol speelt in het faciliteren van transport- en aansluitdiensten, maar dat de huidige netcapaciteit onder druk staat door de groei van duurzame opwekking en elektrificatie. Energy hubs (EH's) worden door Stedin gezien als een tijdelijke oplossing om de beperkte netcapaciteit beter te benutten, vooral in gebieden met congestie. Daarnaast zijn Energy hubs een manier om een brug te slaan tussen netbeheerders en andere stakeholders, zoals bedrijven en lokale overheden. Dit kan bijdragen aan meer bewustzijn en samenwerking tussen partijen die anders geïsoleerd opereren. Hij benadrukt echter dat Stedin momenteel vooral vanuit een reactieve noodzaak betrokken is, bijvoorbeeld om capaciteitsproblemen te mitigeren.

Hoofdvraag 2: Welke taak moet een Energy Hub voor Stedin vervullen?
Optimalisatie van netcapaciteit: EH's kunnen het lokale energiegebruik beter afstemmen en flexibiliteit bieden, wat druk op het bestaande net verlicht. Dit omvat zowel vraagsturing als het benutten van opslagopties.
Vergroten van samenwerking: EH's zouden stakeholders moeten stimuleren om samen te werken, waarbij ***data-uitwisseling*** en ***gezamenlijke planning*** cruciaal zijn. Dit vereist een nieuwe governance-structuur waarin ook gedragsverandering en gezamenlijke verantwoordelijkheid worden aangemoedigd.
Maatschappelijke waarde creëren: Naast technische voordelen benadrukt X dat EH's bijdragen aan bredere maatschappelijke doelen, zoals ruimtelijke ordening en verduurzaming. Dit vereist dat regelgeving en incentives worden aangepast om deze bredere waarde te faciliteren. Er zou een grotere nadruk op het feit dat een EH een middel is en geen doel moeten liggen. Er wordt benadrukt dat EH's vooral een middel zijn om maatschappelijke en economische doelen te bereiken. Dit vereist echter een verschuiving in de mindset van de sector: van een technische naar een meer geïntegreerde benadering.

Hoofdvraag 3: Wat houdt Stedin tegen en wat zijn de drivers om wel mee te doen?

Barrières:
Regelgeving: De huidige wetgeving is sterk gericht op individuele aansluitingen en biedt onvoldoende ruimte voor collectieve oplossingen zoals EH's. X noemt specifiek dat regelgeving rond gesloten distributiesystemen beperkingen oplegt aan de implementatie van EH's.
Financiering: De benchmark-regulering beperkt de mogelijkheid tot proactieve investeringen, wat de implementatie van innovatieve oplossingen zoals EH's belemmert.
Gebrek aan bewustwording: Veel bedrijven en stakeholders zijn zich nog onvoldoende bewust van de voordelen van samenwerking binnen een EH.

Drivers:
Transportefficiëntie: EH's maken het mogelijk om bestaande netcapaciteit beter te benutten, wat directe kostenbesparingen kan opleveren voor de betrokken partijen.
Toekomstgericht beheer: Door flexibiliteit te integreren in het systeemontwerp, kan Stedin anticiperen op de toekomstige energievraag en decentralisatie.
Toekomstperspectief:
De waarde van EH's zit niet alleen in de technische oplossingen, maar vooral in hun potentie om het energiesysteem van de toekomst vorm te geven. Dit vereist dat stakeholders niet alleen reageren op acute problemen, maar actief bijdragen aan een langetermijnvisie waarin EH's een integraal

onderdeel zijn van een decentraal en duurzaam systeem. Hij benadrukt dat dit ook vraagt om flexibelere regelgeving en een proactieve aanpak vanuit de overheid.

Aanvullende inzichten

De noodzaak van flexibele wetgeving

Hij stelde dat er een gedragsverandering nodig is, waarbij netgebruikers en netbeheerders flexibeler omgaan met capaciteitsbenutting en gedeelde verantwoordelijkheid.

Governance- en datavraagstukken zijn hierbij cruciaal: *welke gegevens moeten gedeeld worden om samenwerking en efficiëntie te bevorderen?* Dit vraagt ook om nieuwe governance-modellen.

Er wordt geschetst hoe bestaande regulering vaak innovatie belemmert. Wetgeving is gericht op een stabiel systeem en biedt weinig ruimte voor snelle veranderingen of experimenten.

Deregulering of flexibele wetgeving kan ruimte bieden voor het ontwikkelen van nieuwe oplossingen, zoals Energy Hubs. Dit vereist dat stakeholders eerst samenwerken en ervaring opdoen, voordat wetgeving wordt aangepast aan de praktijk.

Hij pleit voor een marktmodel waarbij nieuwe spelers de juridische ruimte krijgen (zoals CSP's - Congestie Service Providers) om de flexibiliteitsvraag op te pakken en de capaciteitsafnemers te ontzorgen.

Een nieuwe speler en markt

Markt voor nieuwe diensten en rollen

X signaleerde een tekort aan ontwikkelde markten voor flexibele diensten en centrale regie binnen Energy Hubs. Hij verwacht dat nieuwe dienstverleners (zoals CSP's) op termijn belangrijke rollen gaan vervullen, maar waarschuwt voor het risico op monopolievorming.

Toekomst van de rol van netbeheerders

X speculeerde dat de rol van netbeheerders kan verschuiven, bijvoorbeeld door de opkomst van kleinere, commerciële netwerken binnen hubs. Deze netwerken zouden deels zelfstandig kunnen opereren, waarbij de netbeheerder meer een faciliterende rol speelt.

Conclusie

X benadrukte dat Energy Hubs een sleutelrol kunnen spelen in het energiesysteem van de toekomst, mits er voldoende aandacht is voor samenwerking, flexibiliteit en governance. Hij waarschuwde echter dat huidige wetgeving en marktstructuren een belemmering vormen voor innovatie. Om deze barrières te doorbreken, is zowel gedragsverandering als aangepaste regelgeving noodzakelijk. Energy Hubs moeten niet alleen noodmaatregelen zijn, maar bijdragen aan een robuust en maatschappelijk waardevol energiesysteem.

D: Model Information

The dataset containing the model can be found through this DOI: 10.4121/8ca5325a-2db6-4b54-a60f-7b0615d353c4

NAME	DESCRIPTION	UNIT
TIME STEP	Tracks Step Count in model	-
LOAD	Sum of initial transport capacity requirement for the grid	kW
ADJUSTED LOAD	Sum of transport requirement after using flex measures	kW
CONSTRAINT STATUS "NOT OK" PER YEAR	Times where no matter what flex measures are used, the transport requirement exceeds the available capacity	Hours/year
CERTAINTY OF NO CURTAILMENT	Percentage of operating time where all users in the hub do not need to reduce their transport requirement	# of Time steps without curtailment / # of Total amount of time steps
TOTAL CURTAILMENT COST	Sum of costs incurred by grid users to provide flexibility by reducing their transport requirement	€/year
SUM OF GAS LOAD FROM SINK	Amount of gas required for the hub to maintain an energy balance	kWh
SUM OF HEAT LOAD FROM SINK	Amount of heat required for the hub to maintain an energy balance	kWh
AVERAGE ELECTRIC LOAD	Sum of all electricity use divided by total amount of time steps	kWh
TOTAL ELECTRICITY COST	Sum for all steps of (electricity use multiplied by price)	€/kWh
STORAGE LEVEL	Tracks the respective storage level	kWh
STORAGE MUTATION	Tracks change in storage level	kWh
CONVERSION MUTATIONS	Tracks conversion of energy	kWh
SINK/SOURCE MUTATIONS	Tracks required gas/heat energy not consumed or provided within the hub	kWh

Input Parameter Table

Category	Parameter	Description	Defined In
Grid Users	name	Unique identifier for each grid user	load_grid_users()
	electricity_demand_t	Electricity demand profile of the user	
	gas_energy_demand_t	Gas demand profile of the user	
	heat_energy_demand_t	Heat demand profile of the user	
	curtailment_cap	Maximum percentage of load that can be curtailed	
	curtailment_cost	Cost per kWh for curtailment	
Electrical Grid	name	Unique identifier for the grid node	load_electrical_grid()
	grid_electricity_demand_t	Electricity demand at the grid node	
	peak_grid_cap	Peak transport capacity of the grid	
	external_constraint_demand_t	External grid demand constraint	
	external_constraint_supply_t	External grid supply constraint	
	electricity_price	Electricity price profile	
Shared Energy Storage	name	Unique identifier for the storage unit	load_shared_energy_storage()
	medium	Type of energy stored (electricity, gas, heat)	
	energy_capacity	Total energy capacity of the storage	
	max_charge_rate	Maximum charge rate of storage	
	max_discharge_rate	Maximum discharge rate of storage	
	storage_efficiency	Efficiency factor for charging	
	type	Type of storage (battery, thermal, etc.)	
	initial_storage	Initial state of charge	
	minimum_level	Minimum allowable storage level	
	maximum_level	Maximum allowable storage level	
Conversion Units	name	Unique identifier for the conversion unit	load_conversion_units()
	input_medium	Type of energy input (electricity, gas, etc.)	
	output_medium_1	Primary output energy type	
	output_medium_2	Secondary output energy type (if applicable)	
	conversion_rate_1	Conversion efficiency for primary output	
	conversion_rate_2	Conversion efficiency for secondary output	
	min_input_capacity	Minimum input required for operation	
	max_input_capacity	Maximum input capacity	
Sink/Source	name	Unique identifier for the sink/source	load_sink_source()
	Medium	Energy type handled by the sink/source	

Output Parameter Table

Output Parameter	Description
time_step	The current simulation time step.
load	Total aggregated grid user load before any adjustments.
adjusted_load	Load after applying storage management, conversion, and curtailment operations.
supply	The grid's available supply (external constraint) at the time step.
demand	The grid's demand constraint at the time step (typically a negative value in this model).
constraint_status	A status flag ("ok" or "not ok") indicating whether the adjusted load meets grid constraints.
available_cap_supply	Remaining supply capacity, computed as supply - adjusted_load.
available_cap_demand	Remaining demand capacity, computed as demand - adjusted_load.
storage_mutations	A dictionary tracking changes in storage levels from charging/discharging operations.
load_mutations	A dictionary tracking modifications to load due to storage operations.
storage_levels	Current state-of-charge of each storage unit.
flexibility_required	The remaining amount of flexibility needed to meet grid constraints after adjustments.
curtailment	Details of any load curtailment applied to grid users (amount and associated cost).
electricity_price	The electricity price at the current time step, as determined from the grid load profile.
activity_types	The operational status of storage units (e.g., idle, charging, discharging, load management).
conversion_mutations	Changes in energy amounts as a result of conversion unit operations.
sink_source_mutations	Adjustments from sink/source operations to handle excess or deficit energy from conversion.

Formula	Expression	Description
Electricity Price Retrieval	electricity_price = grid.load_profile.loc[grid.load_profile['time'] == time_step + 1, 'electricity_price'].values[0]	Retrieves the electricity price for the current time step (using a +1 offset).

Grid Load Calculation	user_load_sum = sum(user.load_profile.loc[time_step, 'electric_load'] for user in grid_users)	Sums the electricity loads from all grid users at a specific time step.
Available Capacity (Supply)	available_cap_supply = supply - adjusted_load	Computes the remaining supply capacity after accounting for the adjusted load.
Available Capacity (Demand)	available_cap_demand = demand - adjusted_load	Computes the remaining demand capacity (given that demand is negative in your model) after adjustments.
Constraint Check	constraint_status = "ok" if supply >= adjusted_load >= demand else "not ok"	Checks if the adjusted load is within the supply and demand constraints.
Storage Charging	charge_amount = min(max_charge_rate / storage_efficiency, flex_required, energy_capacity - current_storage) actual_charge = charge_amount * storage_efficiency	Determines the charge amount available based on the max charge rate (adjusted for efficiency), flexibility need, and remaining storage capacity.
Storage Discharging	discharge_amount = -min(max_discharge_rate, abs(flex_required), current_storage)	Determines the discharge amount (negative value) limited by max discharge rate, flexibility need, and current storage level.
SOC Balancing (Charge)	desired_charge = min((maximum_level * energy_capacity) - current_storage, available_cap_supply)	Calculates the additional charge required to bring the state-of-charge (SOC) up to the maximum allowed level.
SOC Balancing (Discharge)	desired_discharge = min(current_storage - (minimum_level * energy_capacity), abs(available_cap_demand))	Calculates the discharge needed to avoid dropping below the minimum SOC.
Curtailment for Generation	curtailment_amount = min(abs(user_load), abs(flex_required), curtailment_cap * abs(user_load))	Determines the reduction in generation load when there is surplus (flexibility > 0) based on the curtailment cap.
Curtailment for Consumption	curtailment_amount = -min(abs(user_load), abs(flex_required), abs(curtailment_cap * user_load))	Determines the reduction in consumption load when there is a deficit (flexibility < 0) based on the curtailment cap.

Conversion (Surplus Handling)	input_amount = min(flex_required, max_input_capacity) output_amount_medium_1 = input_amount * conversion_rate_1 output_amount_medium_2 = input_amount * conversion_rate_2	Converts surplus electricity into other energy mediums using conversion unit parameters.
Conversion (Deficit Handling)	desired_input_amount = abs(flex_required / conversion_rate_1) input_amount = min(max_input_capacity, desired_input_amount) output_amount_medium_1 = input_amount * conversion_rate_1	Converts other energy forms into electricity to cover a load deficit.

E: Z score Creation

Synthetic Data Generation Methodology

To address privacy concerns and comply with regulations such as the *Netbeheerdercode*, synthetic data was generated to simulate the original data while preserving statistical relevance. The methodology consists of the following steps:

Calculating Z-Scores: The original dataset was used to calculate z-scores for all data points, standardizing the values relative to their mean and standard deviation.

Adding Noise: To introduce variability, a controlled amount of noise (10% in this case) was added to the z-scores. This step ensures that the synthetic data deviates sufficiently from the original dataset while maintaining the overall statistical structure.

Creating the Synthetic Dataset: A new dataset was generated by defining the synthetic data's desired mean and standard deviation. Using the noisy z-scores, the data points were scaled and shifted according to the previously chosen mean and standard deviation, resulting in a synthetic dataset that mirrors the original dataset's general properties without compromising sensitive information. 60-minute intervals were chosen due to the electrical, gas and price data being in that format.

F: Run Configurations

Scenario	*A0 Dynamic grid + storage*	*A1 Dynamic grid + curtailment & storage*	*A2 Flex with electrification*	*A2b Bigger storage variant*	*A3 Fuel-cell conversion*	*A4 Grid expansion (all-electric)*
Curtailment Cap	A: 30%, B: 50%, C: 10%, D: 0%	A: 30%, B: 50%, C: 10%, D: 0%	A: 80%, B: 50%, C: 10%, D: 0%	A: 80%, B: 50%, C: 10%, D: 0%	A: 0%, B: 0%, C: 0%, D: 0%	A: 0%, B: 0%, C: 0%, D: 0%
Curtailment Cost (EUR/kWh)	A: 2, B: 0.7, C: 30, D: 10	A: 2, B: 0.7, C: 30, D: 10	A: 0.8, B: 0.6, C: 30, D: 10	A: 0.8, B: 0.6, C: 30, D: 10	A: 0, B: 0, C: 0, D: 0	A: 0, B: 0, C: 0, D: 0
Storage Cap (MWh)	2800	2800	2800	5600		
Charge/Discharge (MW)	1400/1400	1400/1400	1400/1400	1400/1400		
Storage Eff. (%)	90%	90%	90%	90%		
Min/Max SOC (%)	0.5 / 0.7	0.5 / 0.7	0.5 / 0.7	0.5 / 0.7	0.5 / 0.7	
Conv. Rate 1 (%)					50%	
Conv. Rate 2 (%)					40%	
Max Input Cap (kW)					2000	

G: MCA Values, Indirect and Deduced Asset Characteristics

Here, the deduced characteristics of the assets are established.

Table With Unmodified Outputs

	unit	A0	A1	A2	A2B	A3	A4
Grid-Constraint Compliance	(Violations / year	11	0	13	2	0	0
Supply Reliability / Business Continuity	Cost in € / year	€ -	€ 20,186.36	€ 337,511.73	€ 144,879.85	€ -	€ -
Congestion Cost / Lack of Access to Transport	Cost until operational	€ -	€ -	€ 1,879,436.00	€ 1,879,436.00	€ 4,698,590.00	€ 1,879,436.00
System Impact	1-5 score	2	3	1	1	4	5
Net Annualized System Cost	Cost in € / year	€ 125,545.89	€ 125,545.89	€ 125,545.89	€ 241,091.78	€ 192,533.16	€ 70,103.98
Total Energy Cost	Cost in € / year	€ 1,479,856.00	€ 1,479,726.00	€ 1,547,012.00	€ 1,547,618.00	€ 1,328,865.00	€ 1,082,911.00
Resource Footprint	1-5 score	3	3	3	1	2	4
Land Use	1-5 score	3	3	3	1	2	4
Governance & Coordinat	1-5 score	3	3	2	2	1	4

ion Burden	

Alternative Outputs

1. Grid Constraint **C**ompliance

Among the different input configurations, only 1, 3, and 4 operated within the grid boundaries. Configurations 0, 2, and 2b were not viable. These values indicate the frequency of grid limit violations.

	Alternative					
	A0	A1	A2	A2B	A3	A4
Grid-constraint compliance (Violations / year)	11	0	13	2	0	0

2. Supply Reliability / Business Continuity

The societal cost of congestion is calculated based on the following formula:

Curtailment hours per year × unit societal cost of congestion

According to Ecorys, this unit cost is composed of four cost components (*kostenposten*), which together represent the total societal impact.

Foregone Added Value (*Gederfde toegevoegde waarde*)

Tholen is home to relatively energy-intensive industries. Based on this industrial profile, the cost of curtailed energy is estimated between **€2,500/MWh** and **€7,500/MWh**, which is significantly lower than the national average of **€11,656/MWh**. For this analysis, a midpoint of **€5,000/MWh** is used. Note: Since local congestion does not hinder residential development in Tholen, **the cost due to lost housing enjoyment (***woongenot***) is omitted**.

Loss of Sustainability Gains

This component reflects missed environmental and decarbonization benefits. A conservative value of **€100/MWh** is used.

Reduced Industrial Competitiveness

Industries face high costs in aligning with climate policy. Congestion disproportionately affects their ability to operate flexibly and remain competitive, often forcing **expensive mitigation measures**. While no exact euro value is assigned here, this category is acknowledged as high impact.

Loss of Renewable Energy Supply

This is valued between €0/MWh and €121/MWh. Given the presence of both import and export congestion in Tholen, and considering Zeeland's oversupply of renewables from offshore wind, €100/MWh is taken as a representative value.
Total Estimated Societal Cost of Congestion

Cost 1 (Foregone Value): €5,000/MWh
Cost 2 (Sustainability Loss): €100/MWh
Cost 3 (Industrial Impact): High impact, non-quantified
Cost 4 (Lost Renewable Energy): €100/MWh
Total Estimated Cost: €5,200/MWh (excluding non-monetized industrial impact)

Applying the social cost of congestion to the amount of energy used the following results are obtained:

	0	*1*	*2*	*2b*	*3*	*4*
Curtailed energy in MWh	0	3.88	64.90	27.86	0	0
Cost in € / year	€ -	€ 20,186.36	€ 337,511.73	€ 144,879.85	€ -	€ -

3. Congestion Cost / Lack of Access to Transport

These are the Annual costs of unmet transport capacity incurred until a structural remedy, such as a hub (e.g., in 2 years, grid reinforcement in 8 years), is in place. Once the asset is in place, this cost is replaced by the congestion cost (factor 2).
The total amount of congestion, assuming no flexibility is measured- meaning that the currently installed storage unit and alternative contracts are excluded- is 180 MWh according to the model. At a price of €5200 per MWh, this would be roughly equivalent to 900 thousand euros.

Yearly congestion in MWh	***180.72***
Yearly cost of congestion	€939,718.00

	0	*1*	*2*	*2b*	*3*	*4*
Expected operational date	2025	2025	2027	2027	2030	2027
Cost until operational	€ -	€ -	€ 1,879,436.00	€ 1,879,436.00	€ 4,698,590.00	€ 1,879,436.00

4. **System Impact**

The system impacts are qualitatively discussed for each asset. Comparing them on a 1-5 scale yield the following results.
Grid reinforcemnt

Grid reinforcement is favored as it completely eliminates the bottleneck. The positive effects are observed at the higher grid level, although there is a risk that congestion may escalate to an even higher level where surplus supply exists in the larger region; this would merely alleviate congestion. Additionally, grid reinforcement would also benefit other users, allowing for greater electrification or renewable integration (TenneT, n.d.).

The hydrogen fuel cell ranks second with 4 points. Although it is still unproven and novel, it aligns well with the replacement of natural gas with hydrogen. Additionally, it is not limited by capacity like electric storage and could serve various roles in the future. The substantial investment required, and the necessary innovation could stimulate the region, positioning it as a leader in the energy transition. While these effects depend on several factors, they hold significant potential.

Third, with 3 points is the current alternative, where both storage and curtailment are utilized. While not creating new grid capacity and maintaining the need for grid reinforcement, they allow local users to continue their operations.

A0 scores two points as it fails to meet the grid constraint compliance criteria, similar to A2 and A2b, but at a much lower cost.

	ALTERNATIVE					
MCA CRITERION	A0	A1	A2	A2B	A3	A4
SYSTEM IMPACT	2	3	1	1	4	5

5. **Net Annualized System Cost,**

The Total annualized CAPEX + OPEX of hub components, deduced from asset-cost requirements per configuration.
To calculate the net annualized system costs, the following method is applied:

- **Sum the capital expenditures (CAPEX)** of the assets included in the configuration.
- **Annualize the total CAPEX** using the Equivalent Annual Cost (EAC) method (Equation 1).
- **Sum the operating expenditures (OPEX)** associated with these assets.
- **Combine the annualized CAPEX and the summed OPEX** to determine the net annualized system cost.

No differentiation is made between current and future price estimates. It is assumed that inflation, rising costs, and efficiency gains approximately balance each other out.
The calculation uses a discount rate (r) of 3%, and a project lifetime (n) of 15 years.

Equation 4, Equivalent Annual Cost

$$\text{EAC} = \frac{P \times r}{1 - (1 + r)^{-n}}$$

Where:
EAC: Equivalent Annual Cost (€ per year)
P: Total initial capital investment (€)
r: Discount rate (e.g., 3% = 0.03)
n: Project lifetime (years)

Example calculation:
For an asset with a total capital cost (P) of €100, an annual operating cost (OPEX) of €10, a discount rate of 3% based on Rapport Werkgroep discontovoet 2020 (Ministerie van Financiën & Inspectie der Rijksfinanciën, 2020), and a lifetime of 15 years based on the intermediary asset life:

Annualized asset cost:
Equation 5, Annualized asset cost

$$\text{EAC} = \frac{100 \times 0.03}{1 - (1.03)^{-15}} \approx €8.37$$

Net annualized system cost:

$$Net\ annualized\ system\ cost = EAC + Annual\ OPEX = €8.37 + €10 = €18.37$$

For this research, these are the assets:

Asset	*2.8MWh storage*	*5.6 MWh storage*	*Fuel Cell*	*Grid reinforcement*
P: Total initial capital investment (€)	€ 1,260,000.00	€ 2,520,000.00	€ 2,000,000.00	€ 240,000.00
r: Discount rate	3%	3%	3%	3%
n: Project lifetime (years)	15	15	15	15
EAC: (€ per year)	€ 105,545.89	€ 211,091.78	€ 167,533.16	€ 20,103.98
OPEX	€ 20,000.00	€ 30,000.00	€ 25,000.00	€ 50,000.00
Total annualized cost	€ 125,545.89	€ 241,091.78	€ 192,533.16	€ 70,103.98

6. Total Energy Cost

The total annual energy cost is calculated as: yearly operating cost = (energy consumed) × (applicable energy price).

Equation 6, Total annual energy cost

$$\text{Annual Energy Cost}_{\text{carrier}} = \sum_{t=1}^{T} E_t^{\text{carrier}} \times p_t^{\text{carrier}}$$

Where:

E_t^{carrier} : Price per kWh of that carrier at time t (€)

T: Total number of hourly time steps (e.g., 8760 for one year)

p_t^{carrier}: Energy consumed in hour t (in kWh) for a given energy carrier

Electricity prices are dynamic and vary hourly. Historical hourly prices from 2023, provided by Jeroen.nl, are used for the simulation.

Gas, heat, and hydrogen prices are assumed to be constant over time. All prices are expressed in €/kWh for comparison across energy carriers. Heat is modeled as **residual heat** in the Tholen configuration and is therefore not priced directly. However, its use reduces the need for other energy carriers and thus indirectly affects the total system energy cost.

Energy Carrier	Assumed Price (€/kWh)	Source/Notes
Natural Gas	€0.14	Based on €1.40/m³ and 10 kWh/m³ conversion
Hydrogen (optimistic)	€0.03	€1.00/kg; ~39 kWh/kg
Hydrogen (PwC estimate)	€0.05	€2.00/kg (PwC, n.d.)
Hydrogen (VEMW 2024)	€0.31	€12.00/kg (VEMW, 2024)
Hydrogen (industrial price)	€0.08	Based on €3.00/kg estimate

Storage, when used for price arbitrage, affects total energy cost by shifting consumption from high-price to low-price hours. It reduces both the total and peak energy cost through time-based optimization, even though its operation is not priced directly.

Energy price variability is explored based on PwC (n.d.), VEMW (2024), and ACM reports. Energy conversion is expected to eliminate alternatives where prices between energy carriers vary significantly and structurally.

High and low price estimates are used to test the robustness of alternatives. Alternative A4 is shown to be the **least sensitive** to energy cost variation while remaining the most favorable in outcome. For the various alternatives, the resulting energy costs are:

Flexibility Cost	*0*	*1*	*2*	*2b*	*3*	*4*

Central energy price	€ 1,479,856	€ 1,479,726	€ 1,547,012	€ 1,547,618	€ 1,328,865	€ 1,082,911
low Energy Price	€ 413,876	€ 413,789	€ 458,647	€ 459,051	€ 802,551	€ 721,941
High	€ 3,313,110	€ 3,312,915	€ 3,413,844	€ 3,414,754	€ 2,618,488	€ 1,624,367
Average Cost	€ 1,735,614	€ 1,735,477	€ 1,806,501	€ 1,807,141	€ 1,583,302	€ 1,143,073

Criterium 7, 8 and 9. Resource Footprint, Land use and Governance burden

Resources have been evaluated qualitatively on a scale from 1 to 5, with higher scores indicating the use of less critical resources. Similarly, land use and governance burdens have been assessed based on the asset description.

	Alternative					
MCA criterion	A0	A1	A2	A2B	A3	A4
Resource footprint	5	3	1	1	2	4
Land use	5	3	3	1	2	4
Governance Burden	5	3	2	2	1	4

Asset Characteristics

2.8 MWh Storage

3. Congestion Cost / Lack of Access to Transport: Annual cost of unmet transport capacity, incurred until structural remedy (e.g. hub in 2 yrs, grid reinforcement in 8 yrs).

In Tholen, storage is already in place, making the solution immediate. Typically, container-based lithium-ion storage systems take 1 to 2 years to become operational (Mulder and Klein, 2024)

4. System Impact: Qualitative assessment of broader system effects (innovation spillovers, market structure shifts, long-term transitions).

- Short-term use only: Electricity storage works well for quick, short duration support due to low conversion losses.
- Not for strategic reserves: Limited capacity and duration make storage unsuitable for long-term backup (EZK, 2023).
- Suited for energy trading if transport capacity allows it, possibly reducing energy costs.

- Could enable local flex trading markets.

5. Net Annualized System Cost: Total annualized CAPEX + OPEX of hub components, deduced from asset-cost requirements per configuration.

CAPEX costs vary significantly and are expected to fluctuate in the future. According to *Routekaart Energieopslag*, the expected range lies between €380 and €700 per kWh (EZK, 2023). For lithium-ion storage systems of similar capacity, OPEX is typically estimated at approximately 1.5% of the CAPEX (Streuling et al., 2021). However, operational costs can also depend heavily on site-specific conditions, such as enforced safety protocols and maintenance schedules.

7. Resource Footprint: Monetized environmental impact of raw-material use, using societal-cost estimates per unit of material consumed.

The battery energy storage system (BESS) requires a significant number of raw materials, many of which fall under the scope of the European Raw Materials Act. This is roughly 1,100 kg of graphite, 833 kg of lithium, 633 kg of nickel, and 200 kg of cobalt per megawatt-hour (Lebrouhi et al., 2022).

8. Land Use: Spatial requirement deduced from physical footprint of infrastructure and planning-constraint allowances.

The container, including the safety perimeter and transformer, would occupy approximately 100 m². This aligns with typical estimates of 30–80 m² per MWh of storage capacity, as cited in current energy storage planning guidelines (EZK, 2023).

9. Governance & Coordination Burden: One-time transaction costs (contracts, legal) + recurring coordination costs (data exchange, compliance monitoring).

- Low to medium general burden: Grid code compliance is straightforward and fits within existing contracts.
- Balanced planning is required: All grid users must submit a day plan at 15-minute intervals or designate a responsible party.
- No legal definition: Storage is not defined in the Electricity Act, leading to regulatory gaps.
- Unfavorable tariffs: Peak-based pricing penalizes short-term storage usage, increasing costs.
- Non-firm ATOs are restricted: Not formally permitted; only tolerated on a case-by-case basis, which limits flexibility.

Curtailment

3. Congestion Cost / Lack of Access to Transport: The annual cost of unmet transport capacity incurred until a structural remedy is implemented (e.g., hub in 2 years, grid reinforcement in 8 years).

Curtailment can, in theory, be applied immediately. For the Tholen case, the contracts and congestion service provider are already in place, which means that only the grid users/ companies have to deliberately adjust their usage and adapt their operations. In practice, when the specific contracts and CSPs are not yet in place, it will take at least a year before all is set up.

4. System Impact: Qualitative assessment of broader system effects (innovation spillovers, market structure shifts, long-term transitions).

- Low-cost grid relief: Curtailment reduces renewable output during peak supply to prevent overload.
- Does not independently resolve congestion
- No storage losses: Energy is simply not produced, avoiding conversion or storage losses.
- Limited flexibility: Only a portion of generation can be curtailed.
- Enables leaner grid design: Helps minimize the need for over-dimensioning grid infrastructure. Perceived as wasteful: clean energy or transport capacity is lost.

5. Net Annualized System Cost: Total annualized CAPEX + OPEX of hub components, deduced from asset-cost requirements per configuration.
The system cost is very low, primarily comprising just control and monitoring equipment. Capital expenditure for curtailment, which includes software and firmware, is minimal, resulting in an annual cost close to €0.

Curtailment costs are included in the model as a direct penalty for the amount of energy that cannot be transported due to grid constraints. These costs are use-specific and are calculated based on the volume of curtailed energy and the cost associated with curtailing that particular user.

Equation:

Equation 7, Curtailment costs

$$\mathrm{C_{curt}} = \sum_{\mathrm{i=1}}^{\mathrm{N}} \left(E_{\mathrm{curt},i} \times c_{\mathrm{curt},i} \right)$$

Where:

- C_{curt}: Total curtailment cost (€)
- $E_{\mathrm{curt,\,i}}$: Curtailed energy for user i (in kWh)
- $c_{\mathrm{curt,\,i}}$: Curtailment cost rate for user i (€/kWh)
- *N:* Total number of curtailment users

Implementing the formula gives the following results, when curtailment is not part of the strategy, the costs are 0.

Alternative	***0***	***1***	***2***	***2b***	***3***	***4***
User Curtailment Cost	€ -	€ 523.72	€ 8,371.26	€ 4,166.03	€ -	€ -

7. Resource Footprint: Monetized environmental impact of raw-material use, using societal-cost estimates per unit of material consumed.
Negligible. Curtailment uses no additional equipment beyond controls, no material footprint beyond existing inverters and IT.

8. Land Use: Spatial requirement deduced from the physical footprint of infrastructure and planning-constraint allowances.
None: uses existing infrastructure.

9. Governance & Coordination Burden: One-time transaction costs (contracts, legal) + recurring coordination costs (data exchange, compliance monitoring).
Low to medium. Primarily a DSO-driven measure: rules for curtailment are straightforward (often "emergency curtailment" clauses exist). Little new contracting is needed beyond upgrading grid codes. (No new assets to permit.) However, the curtailment strategy places some system responsibility on grid users, who in turn become dependent on each other. If one user fails to comply, this negatively impacts the others, exposing them to new risks they otherwise would not face. This means a shift in mentality regarding energy transport access: Not all capacity is always available, departing from the originally regulated idea that the operator would not decide when transport capacity can be used.

Fuel Cell

3. Congestion Cost / Lack of Access to Transport: Annual cost of unmet transport capacity, incurred until structural remedy (e.g. hub in 2 yrs, grid reinforcement in 8 yrs).
The Tholen case only addresses the conversion asset, intentionally omitting the necessary hydrogen infrastructure from consideration. It assumes that hydrogen will be delivered in the same manner as natural gas currently is. Routekaart Energieopslag estimates that at least five years are needed to utilize a hydrogen fuel cell (EZK, 2023).

4. System Impact: Qualitative assessment of broader system effects (innovation spillovers, market structure shifts, long-term transitions).

- Adds long-duration, sector-coupling flexibility; accelerates H_2 infra roll-out.
- Constant power and heat supply: Delivers 1 MW of electricity and 0.8 MW of low-temperature heat, unaffected by storage duration.
- Supports peak shaving, which reduces grid load during high-demand periods (used ~50–100 hours/year in backup mode).
- High fuel demand + emissions: Increases hydrogen use and produces local NOx and steam emissions.
- No energy storage function: It does not store energy and only converts molecules to electricity on demand.
- Mid-/long-term balancing: Suitable for seasonal energy shifts and strategic reserves (e.g., hydrogen, ammonia, methanol).
- Storage challenges: Requires cryogenic temperatures (liquid) or high-pressure tanks (gas); costly and technically complex.
- Growing importance: Hydrogen is key in all future energy scenarios (2030–2050), especially for imports and buffering.
- Infrastructure in progress: No mature H_2 market yet; EU market rules are under development. Social acceptance needed: Storage (e.g., salt caverns) and above-ground handling (e.g., ammonia) raise safety and public concerns.

5. Net Annualized System Cost: Total annualized CAPEX + OPEX of hub components, deduced from asset-cost requirements per configuration.

The estimated costs vary significantly; estimations place the costs at €1,000–€5,000/kW, translating to a total of €1 million to €5 million. A price estimation of €2 million was used.
The consensus is that prices are expected to be substantially lower in the future.

According to Xu et al., prices were anticipated to drop to $3000 and $2000 per kW in 2020 and 2025 respectively (Xu et al., 2020). Cigolotti et al. report that the current picture presents a value between € 2000 and € 3,500 per kW, and the economy of scale is projected to reduce the cost to € 1200–€ 1,750 per kW (2021).

7. Resource Footprint: Monetized environmental impact of raw-material use, using societal-cost estimates per unit of material consumed.

Mori et al. notes that the basic critical raw materials needed for a typical SOEC cell are nickel (200 kg/MW), zirconium (40 kg/MW), scandium (23 kg/MW), lanthanum (20 kg/MW), and yttrium (5 kg/MW). Through design improvements (2021), the material requirements are expected to be halved over the next decade.

8. Land Use: Spatial requirement deduced from physical footprint of infrastructure and planning-constraint allowances.
Two 20-foot containers, approximately 140 m², including a safety perimeter.

9. Governance & Coordination Burden: One-time transaction costs (contracts, legal) + recurring coordination costs (data exchange, compliance monitoring).

- High overall burden: Requires contracts for gas or hydrogen, safety permits, and heat offtake agreements.
- Safety regulations: Strict standards for hydrogen or derivative storage (e.g., liquid hydrogen, ammonia).
- Subsurface risks: Underground H_2 storage (e.g., in salt caverns) can lead to land subsidence.
- Long-term planning needed: Involves future capping and safe closure of caverns, sourcing brine to refill.
- Social and technical acceptability: Aboveground infrastructure and risks must be deemed acceptable by society and regulators.

Grid reinforcement

3. Congestion Cost / Lack of Access to Transport: Annual cost of unmet transport capacity, incurred until structural remedy (e.g. hub in 2 yrs, grid reinforcement in 8 yrs).
According to Stedin, the planned reinforcement will be operational in 2027.

4. System Impact: Qualitative assessment of broader system effects (innovation spillovers, market structure shifts, long-term transitions).

- Solves local congestion: Fully removes bottlenecks at the distribution level.
- No behavioral change needed: Grid users can maintain normal consumption patterns.
- Shifts pressure upward: May move congestion risk to high-voltage and transmission networks.
- Future-proofing: Extra capacity could support future electrification and system needs.

5. Net Annualized System Cost: Total annualized CAPEX + OPEX of hub components, deduced from asset-cost requirements per configuration.

It is assumed that the prices charged by grid operators closely reflect the true cost on average, as intended by the ACM. The pricing varies slightly but is tightly regulated by the ACM. According to Stedin, Enexis, and Alliander:

Up-front investment

- Connection fee (aansluitkosten): ≈ € 80,000
- Customer substation (klantstation): ≈ € 160,000
- Total Grid Investment Costs: ≈ € 240,000

Recurring annual charges

- Fixed connection charge (periodieke aansluitvergoeding): ≈ € 2 000 yr^{-1}
- Fixed transport tariff (vastrecht): € 230 $month^{-1}$ ≈ € 2 760 yr^{-1}
- Variable transport tariff: € 3.79 kW^{-1} $month^{-1}$ × 1 000 kW ≈ € 45 480 yr^{-1}

7. Resource Footprint: Monetized environmental impact of raw-material use, using societal-cost estimates per unit of material consumed.

12 t Cu-Al for 1 km 3×240 mm² cable; 5 t steel and 2 t oil in transformer

8. Land Use: Spatial requirement deduced from physical footprint of infrastructure and planning-constraint allowances.

The extra switchgear yard is approximately 50 m² at the hub; the cable route utilizes the existing right-of-way. (30 m² building plus additional space.) An additional 1% of high-speed medium-voltage stations; 0.01*(125 m* 250 m) is approximately 300 m² of extra space on a medium-voltage station. This brings the total space to around 320 m². However, since the space requirements for the other assets have been confined to direct and singular use, only the additional direct space requirement of 50 m2 has been taken into account.

9. Governance & Coordination Burden: One-time transaction costs (contracts, legal) + recurring coordination costs (data exchange, compliance monitoring).

- Low burden overall: Business as usual for users; investments are made by the DSO and are regulated.
- Stable regulation: Tariff structures are known, standardized, and broadly accepted.
- No added complexity: No need for new laws, contracts, or CSP.
- Clear responsibilities: Roles and duties are well-defined within existing institutional frameworks.