Energy Hubs' Contribution to Network Management

MSc Sustainable Energy Technology Thesis Project

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by

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Cover: Digital generated image of wind turbines, solar panels and Hydrogen containers standing on landscape against blue sky from Getty Images (Modified)

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Abstract

As the transition towards a sustainable energy system gains momentum, the concept of energy hubs has emerged as a promising solution to make the existing energy system more efficient. This thesis aims to investigate the contribution of energy hubs to network management in the Dutch energy system. The research questions focus on identifying the key components and objectives of energy hubs, understanding the roles and interests of stakeholders involved, assessing the effectiveness of energy hubs in achieving policy goals, and exploring the opportunities and threats they present to the Distribution System Operator (DSO).

The study employs a mixed-methods approach, combining theoretical analysis, stakeholder interviews, SWOT analysis, and case studies. Through a comprehensive literature review, a holistic understanding of energy hubs is established, providing a foundation for further analysis. Stakeholder interviews offer insights into the perspectives and interests of various actors in the energy sector, shedding light on the roles they play and the potential benefits of energy hubs.

The thesis analyses the theoretical and practical value of energy hubs, considering their potential to optimise network capacity, enhance renewable energy integration, and improve system flexibility. SWOT analysis allows for a thorough examination of the strengths, weaknesses, opportunities, and threats associated with energy hubs. The analysis of case study projects further enriches the findings by providing real-world examples and highlighting their applicability in practice.

The results demonstrate that energy hubs have the potential to contribute significantly to network management, offering benefits such as reduced grid congestion, increased renewable energy utilisation, and enhanced collaboration among stakeholders. However, limitations exist, including the need for a clear definition, standardised legal procedures, and a comprehensive understanding of the specific conditions under which energy hubs are most suitable.

This thesis contributes to the existing knowledge on energy hubs and their impact on network management. It offers a comprehensive analysis of their key components, stakeholder dynamics, policy implications, and practical considerations. The research findings provide valuable insights for both academia and industry, informing future research directions and aiding DSOs in harnessing the full potential of energy hubs to facilitate the transition towards a sustainable and resilient energy system.

Contents

List of Figures

List of Tables

Abbreviations

Abbreviation	Definition
AC	Alternating Current
ACM	Autoriteit Consument en Mark, in English: Authority for Consumers and Markets
ATO	Afsluit-en Terugleveringspunt Overeenkomst, in English: Disconnect and Feed-in Point Agreement
BAU	Business as Usual
CDS	Closed Distribution System
CHP	Combined Heat and Power
CO_2	Carbon Dioxide
CoOs	Certificates of Origin
CPA	Cable Pooling Agreement
DC	Direct Current
DSO	Distribution System Operator
DER	Distribution Energy Resource
E-Act	Electricity Act
ECUB	Energie Collectief Utrechtse Bedrijven, in English: Energy Collective Utrecht Companies
EH	Energy Hub
GoOs	Guarantees of Origin
KPI	Key Performance Indicators
MES	Multi-energy Systems
MILP	Mixed Interger Linear Programming
MINLP	Mixed Interger Non-Linear Programming
PV	Photovoltaic
SOC	State of Charge
SRQ	Sub-Research Question
SWOT	Strengths, Weaknesses, Opportunities, and Threats
TSO	Transmission System Operator
VPP	Virtual Power Plant

1 | Introduction

The increase introduction of renewable energy into the electricity grid causes grid congestion problems amongst other undesirable effects for grid managers. The current energy system is not designed for the intermittent nature associated with distributed energy resources (DERs) and their deployment threatens the stability of the energy grid. The high levels of congestion experienced in the Dutch electricity grid is preventing the realisation of generation capacity. Moreover, there is also a need to future proof the energy system through encouraging the use of different energy carriers and introducing more storage to deal with the inherit limitations of DERs. Expanding of the generation capacity, and transmission capacity of the grid is a timely, costly and complex undertaking considering the requisites accompanied by the changing energy landscape, therefore other approaches should be considered.

To develop the energy system sustainably, a fitting use of the different energy carriers is necessary (Lasemi et al., 2022). This is further backed by the II3050, 2021 report, presenting a long-term vision of a future energy system which combines various energy carriers. With the advancement towards a multi-carrier energy system (MES), a relevant tool is necessary for the efficient management of the integrated system components. Energy hubs (EHs) pose as a possible solution in modernising network management and facilitating the transition towards a more varied energy mix. An EH has no set definition, however, in essence, it is a geographically limited, decentralised network, where different energy carriers (including electricity, gases, molecules, and heat) are interconnected in an optimised way and can be converted, conditioned and/or stored. It acts as an interface connecting different input and output nodes of the different energy carriers and optimises their usage to meet the different types of energy demands in the designated area.

EHs can highly affect the energy network, therefore are a topic of great interest for network operators. Stedin is the distribution system operator (DSO) of the the Province of Utrecht, Zeeland, and the major part of South Holland; as such, it has the obligation to provide connections to its electricity and gas network. Although in literature it is found that EHs increase the efficiency of their multi-energy carrier systems, their complexity brings additional responsibilities for energy system managers. The purpose of this thesis is to get a deep comprehension of energy hubs in order to analyse what societal benefits these may bring. Subsequently it aims to facilitate Stedin in thoroughly understanding what its position should be towards energy hubs and to assist Stedin in its strategy definition towards energy hubs.

Chapter 2 gives background on the energy system in the Netherlands, in order to contextualise and provide the necessary foundations. This is followed by the research questions that will be addressed in this report in chapter 3, and the methods used to analyse these questions in chapter 4. Chapter 5 analyses the theoretical value of energy hubs. This is built on with chapter 6 that brings a real world perspective of the value of EHs through looking at two case studies. Chapter 7 takes the gathered information to answer all the research questions. The conclusion, in chapter 8, reflects on the value this project brings and on future research that can still be done on the topic.

2 | Context on the Dutch Energy System

This chapter provides background knowledge necessary to contextualise the reader on the energy system in the Netherlands. It first describes the energy system from a physical perspective by looking at the infrastructure in section 2.1. Section 2.2 looks at the legislative climate of the energy system in the Netherlands by providing detail on the roles of different facilitators and on the frameworks in place for the development of renewable energy projects. Finally section 2.3 provides detail on emerging energy concepts.

2.1. Infrastructure

TenneT is the Netherlands' only electricity transmission system operator (TSO) and therefore is the sole entity responsible for operating the grids transmission network (voltages > 110kV), it also operates in some parts of Germany. Networks with a voltage less than 110kV make up the grid's distribution network, this network is owned by local authorities and managed by the 6 different DSOs: Cogas Infra en Beheer B.V., Liander N.V., Enexis B.V., RENDO Netbeheer B.V., Stedin Netbeheer B.V. and Westland Infra Netbeheer B.V. (CMS, 2015).

The electricity network is designed in a hierarchical structure, with large-scale electricity generation being transported through the transmission grid, and then through the distribution grid down to the consumers. The the addition of DERs (e.g. solar and wind power generation) is straining the grid due to the traditional grid design. This causes problems including grid congestion, voltage issues, need for power curtailment, a loss of inertia, uncertainty of market behaviour, amongst others (Alpízar Castillo et al., 2022). Different instruments to overcome these challenges must be incorporated into the energy system in order to facilitate the further introduction of renewable energy sources. Emerging concepts that aim to modernise the grid structure are presented in section 2.3. A map of the electricity grid of the Netherlands is presented in figure 2.1 to visualize th complexity of the electricity system.

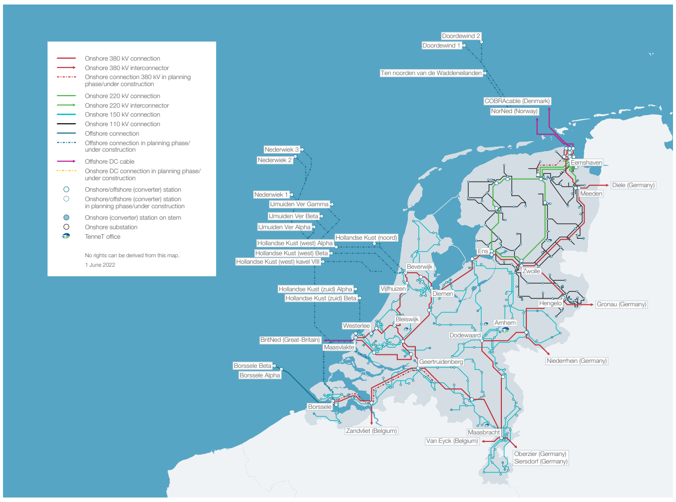

Figure 2.1: Electricity Grid Map of the Netherlands (TenneT, 2022)

Gasunie is an energy network operator that manages the infrastructure for large-scale transportation and storage of gases in the Netherlands (and some parts of Germany). The Dutch gas infrastructure is very mature, with natural gas as its main transportation matter. However, due to trends towards decentralisation and a movement towards cleaner gases, expansions and changes to the gas network should be made (Riemersma et al., 2020). Gasunie suggests that for stable and flexible future energy system, a smart control of an inevitable varied energy mix is needed (Gasunie, 2023), further confirming the need for multi-energy carrier systems.

2.2. Legislation

The principal actor in the energy sector is the Minister of Economic Affairs and Climate Policy (the Minister). The Minister is in charge of making a strong entrepreneurial business climate through ensuring the right conditions that will allow room for growth and innovation (Government of the Netherlands, n.d.).

European legislation and the Dutch Electricity Act (E-Act) has highly shaped the current Dutch governmental policies and legislative framework for the energy sector. The E-Act came into effect in 1998, implementing the First Energy Package of European energy legislation, and serves as a foundation for electricity policy in the Netherlands. Since then it has gone through amendments, including the implementation of the Second Energy Package in 2004, and the Third Energy Package in 2012, which allowed the unbundling of the electricity network (CMS, 2015). The E-Act sets out legislation for the production, transportation, and supply of electricity, moreover, it defines the powers and obligations of the ACM (Autoriteit Consument en Mark) - the dutch energy regulator, responsible for the independent supervision of the energy market.

The ACM has the interest to safeguard energy customers by regulating network operators, including Stedin. DSOs act as a monopoly within their designated operation area, therefore need an independent entity to supervise their operation to ensure fair pricing to their customers. The ACM does this through determining the maximum yearly prices that the DSOs are allowed to charge for their services (ACM, 2023), directly influencing the revenue that the DSO is able to make, therefore ensuring an efficient operation by the DSO. The ACM must also allocate enough revenue to the system operators so that they are able to provide a good quality and reliable service (CMS, 2015).

Through the unbundling of the energy network as required by the Third Energy Package (European Commission, 2023), generation, supply and trading companies became privatised, however still publicly controlled (CMS, 2015). The amendment in the E-Act ensures that network operators are not allowed to cooperate with any commercial company or to engage in any activity that may be a conflict of interest to their operation. This separation ensures that entry to the energy network can happen in a non-discriminatory manner, as incentives to prioritize certain market players are thus removed. After the inclusion of the Third Energy Package to the E-Act, system operators are obliged to act as a neutral market facilitator to anyone wanting to connect to their network; meaning identical terms and conditions of entry for any and all market players. Anyone has free market rights of connection, contracting, and dispatching in the Dutch energy network. The absolute right to connect to the grid is done by the system operator, meaning these costs are socialised and individuals do not feel this cost. In the current energy network customers have unrestricted behaviour.

The ATO (”Aansluit- en transportovereenkomst”, in English: connection and transport agreement) is a connection agreement between the functioning system operator and the party that wishes to be connected to the grid (customer or producer)(Netbeheer Nederland, 2021). The agreement covers necessary aspects, including technical requirements of the connection, safety measures, metering arrangements, and the responsibilities of each side, in order to ensure a stable, reliable, and standardised connection. This legal framework establishes clear guidelines for the connection. It is becoming increasingly difficult for a party to secure an ATO due to congestion in the grid, consequently, in places where a connection is not possible, the connection request enters a queue. This queue works in a first come first served basis, where, if/when capacity opens up, the first arrival is allocated the ATO.

There are various regulatory frameworks in place to aid the development, financing, operating, and selling power for renewable energy projects. These include (Dewar et al., 2023):

- E-Act and Gas Act - these provide legislation on what technical conditions must be met, on tariffs, and on procedures on system access.
- The phase out production of natural Groningen gas by 2030.
- Heat Act - regulates the Dutch heat supply market.
- Wind Energy Act - establishes a specific licensing regime for off-shore wind plants.
- SDE++ - subsidy that supports renewable energy projects and (carbon dioxide) CO_2 reduction projects.
- Energy taxation - users of renewable energy are exempt from paying tax for their energy consumption.
- Guarantees of Origins (GoOs)/Certificates of Origins (CoOs) - these are certificates, issued by CertiQ (subsidiary of TenneT), that prove the origin of the energy generation. These are necessary for subsidy application.

All these frameworks are put in place to accelerate the transition through providing a clear, standardised approach to allocating help to the development of renewable energy and low carbon projects.

2.3. Emerging Energy System Concepts

In the context of EHs, other concepts are often used. Although, at times these different concepts are closely related, and may also be used to define the same thing, they are applied in different contexts or perspectives. Distinguishing between them is very important not only to gain a more clear understanding of the definition of each, but also to understand the differences between them and energy hubs. Therefore this will allow the analysis of whether the EH concept brings innovation to the energy network, or if it is just another word to describe already existing concepts.

2.3.1. Smart Grids

The word ”smart” when it come to energy systems, is a characteristic given to a system that has a control with the ability of data integration, system monitoring, reliable data communication, secured data analysis, and local and supervisory controls (Al-Badi et al., 2020). Such a system can intelligently harmonise the behaviour of all its connections, resulting in an efficient delivery of sustainable, economic and secure electricity supply.

Any network that has such a control can be classified as ”smart” and therefore is not limited to other criteria such as geography or types of network systems. An EH and a smart grid are not mutually exclusive, actually on the contrary, EHs tend to have a smart control, as this allows for further optimisation of the system through increased information of system components.

2.3.2. Microgrids

A microgrid can be defined as a system of interconnected loads, distributed energy resources, and storage devices that act as a single controllable entity that can operate in both grid-connection mode or autonomous mode (Ton & Smith, 2012).

Microgrids that have an optimisation control strategy with conditioned inputs can be themselves also considered a larger-scale energy hub, as they already satisfy the other conditions of being geographically limited and having a central control unit (see section 5.1.1 for all limiting criteria of an EH). However not all EHs can be treated as microgrids as there are further technical requirements that microgrids must comply with to operate in island/autonomous mode (disconnected from the main network grid). To operate autonomously from the grid, the microgrid must provide system stability, reliability and operational control. In order to do that, the system has to consider various technical challenges, for example in power balancing. Common microgrid components have low inertia and a slow dynamic response meaning other flexibility technologies (such as storage systems or demand response) must be added to overcome these issues. Another consideration is the need for a device to ensure the voltage synchronisation when connecting the autonomous microgrid back to the main grid (Choudhury, 2020). Microgrids may contain EHs inside of them also, literature that considers both concepts look at how the EH concept can be used as an optimisation strategy for a microgrid (Jalili et al., 2021; Shams et al., 2019).

2.3.3. Closed Distribution System (CDS)

A closed distribution system (CDS), Gesloten Distributie Systeem (GDS) in Dutch, is a private electricity and/or gas network made using an exemption from the obligation to designate a network operator. In order to apply for this exemption by the ACM and be able to build a CDS, the developer must comply with set legal conditions (ACM, 2023) . Firstly, the network must have a defined geographical area. Secondly, a maximum of 500 customers are allowed to be connected to the network, and these are not allowed to be household-customers. Finally, the connection between production and the customers must be in a integrated system, for technical or safety reasons.

A key distinguishing technical characteristic of a microgrid and a CDS is the microgrid’s ability to operate in island mode. With this comes several technical difficulties that CDSs do not need to comply with as they have a constant point of connection to the grid. Moreover, the classification of a CDS exists under dutch law, whereas that of a microgrid is a technical definition recognised in the field however lacks legal recognition.

Like microgrids, CDSs may have energy hubs within them or the whole of the CDS may also be an EH, assuming the other criteria is met. Since this paper takes the energy system operator as the problem owner, energy hubs within CDSs are not further analysed.

2.3.4. Virtual Power Plants (VPPs)

A VPP is an aggregation of DER units dispersed among the network (not geographically limited) but managed as a whole generating system, acting as a singular entity in the energy market (Wang et al., 2019). Since the generation units of VPPs are dispersed across the electricity network these may not also be considered energy hubs (as EHs are geographically limited). In the case that the VPP is geographically limited and includes other energy carriers (other than electricity) it may also be considered an energy hub as it satisfies the EH definition (see section 5.1.1).

In order to further differentiate VPPs, they are compared to microgrids; the key differences between VPPs and microgrids include:

- Locality: In microgrids, all system components are located within a local distribution network, whereas in VPPs, components are virtually coordinated over a wide spread of locations.
- Size: VPPs may reach a much higher installed capacity of DERs or other energy sources.
- Consumer involvement: Microgrids must be able to satisfy all of the demand connected to its network, whereas VPPs view demand as a flexible resource.

2.3.5. Congestion Management

Congestion management is a procedure that the network operator must take when an area is identified as congested. This procedure tries to make better use of the existing capacity through adjusting the consumption patterns of the involved parties.

Once the load (current plus expected) in an area comes very close to the maximum capacity of the limiting component in the system (either the cables, or the substation), then the DSO must monitor the developments in the area more closely. If then further demand is requested that goes beyond the system capacity, then the DSO must ”announce the area as congested”. From this point, any additional demand/connection requests must enter a queue. Once the DSO announces congestion, then research on the possibilities to overcome this congestion should begin.

The grid code expects several steps. The DSO should initially try to find a market based solution through examining the involved parties’ willingness to adjust their energy usage in exchange for a compensation from the DSO. If the DSO is not able to find sufficient flexible power to meet the technical and financial requirements then it must enter the next stage. In the next stage the DSO ”summons” the parties to ”make an offer”. If that is not possible, or does not result in the technical and financial requirements to be met, then the congestion management enters its last phase, where non-market based strategies are used. This final stage is a last resort in getting the involved parties to alter their consumption.

The compensation that the DSO is able to give the involved parties is established in the contracts made with the flexibility providers. It changes case by case, but in order for the flexibility provider to agree to the contract, the compensation should be above the income that they would have otherwise generated.

2.3.6. Cable Pooling

Cable pooling is becoming an increasingly popular solution to overcome grid congestion problems in the Netherlands. Essentially it is the 'pooling' of the connection capacity; this means that multiple generation capacities are able to be connected to the same point (Priogen, 2022). This strategy is greatly beneficial and currently mostly used when combining solar and wind generation due to their anti-correlation generation profiles. This allows making more use of the specific capacity of the cable connecting the already existing generation due to its limited capacity factor (Golroodbari et al., 2021), as seen in figure 2.2. The diagram on the left shows a wind plant and a solar plant connected in a traditional fashion, compared to a cable pooling connection shown on the diagram on the right. Even though wind and solar combination are the most common form of cable pooling, other system architectures can be made too, for example, solar on solar, by changing some design parameters.

Cable pooling increases the simplicity of the electricity market overall by providing a more balanced annual generating profile (Green Partners, 2022). This may not be a concern of the project developer, but is a benefit for the grid which is why the cable pooling agreement (CPA) has been accepted (windpowernl, 2022).

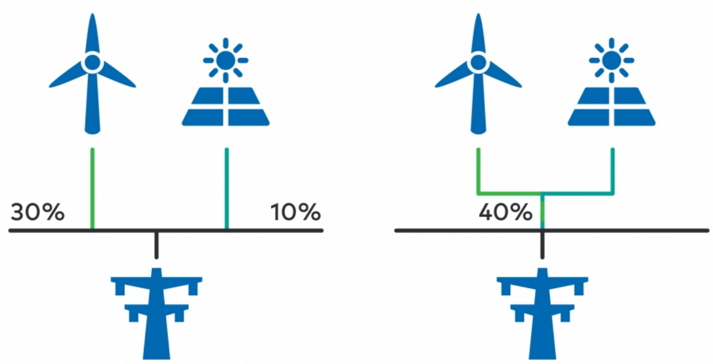

Figure 2.2: Cable Pooling Diagram (van de Vegte, 2021)

3 | Research Questions

Research shows EHs lead to a more optimal usage of components, bringing flexibility to the energy system. The synergy between the energy carriers is also viewed as a benefit due to the increased efficient usage of each carrier. In literature, many advantages attributed to EHs are expressed with the main advantage being the increased efficiency leading to the optimal use of energy resources, reduced system cost, and a reduction in carbon emissions (Mohammadi et al., 2017). Bozchalui et al., 2021 back this up with a simulation showing a reduction in residential energy costs of up to 20%, without decreasing the residents' comfort level. Another advantage highlighted in literature is the possible substantial reduction in grid congestion leading to reduced costs and time of upgrading the energy network (Hu et al., 2021).

Theoretically it is clear that the EH model brings technical advantages to the energy network. However, there is a lack of understanding of how these advantages are experienced practically resulting in a lack of understanding of the real value of energy hubs. This knowledge gap holds particular significance for Distribution System Operators (DSOs), as it is of interest for them to comprehend how these factors can contribute to enhancing their operational efficacy. Academic literature offers limited insight into the pragmatic advantages EHs confer upon both network operations and the stakeholders involved. This lack of understanding creates uncertainty among network operators, which in turn hinders the smooth adoption of this emerging model into their established ways of operating. As such, this research aims to address the prevailing knowledge gap and examine how the introduction of energy hubs might either facilitate or hinder the endeavors of network operators, encapsulated within the research question:

How can energy hubs contribute to network management in the Dutch energy system?

The following sub-research questions aim to help answer the main research question, by breaking it down:

1. What are the key components and objectives of an energy hub?
2. Who are the actors involved, what are their roles, and how can they benefit?
3. What makes EH a successful tool in achieving policy goals important to the DSO?
4. In practice, what opportunities and threats do EHs present to the DSO?

4 | Methodology

This chapter presents the methodologies employed to effectively analyse the research question. Firstly, a description of the research flow of the whole project is given in section 4.1. The data gathering methodology comprises of different sources, these are described in section 4.2. Finally, section 4.3 describes the approaches used to analyse the collected data.

4.1. Research Flow

Figure 4.1 shows the different techniques used in the different chapters and what outputs are aimed to be achieved. The research flow diagram provides a visual representation of the research process, showing a logical flow of activities from the initial presentation of the research questions to the final analysis and interpretation of the data gathered. It serves as a road-map to help researchers and readers understand the overall structure and progression of the research, highlighting key topics, methodologies used, and outputs of the research. Presenting the research flow this way enhances transparency, reproducibility, and the integrity of the thesis. It facilitates the ability to identify potential gaps or flaws in the methodology and enables effective communication of the research process to the audience.

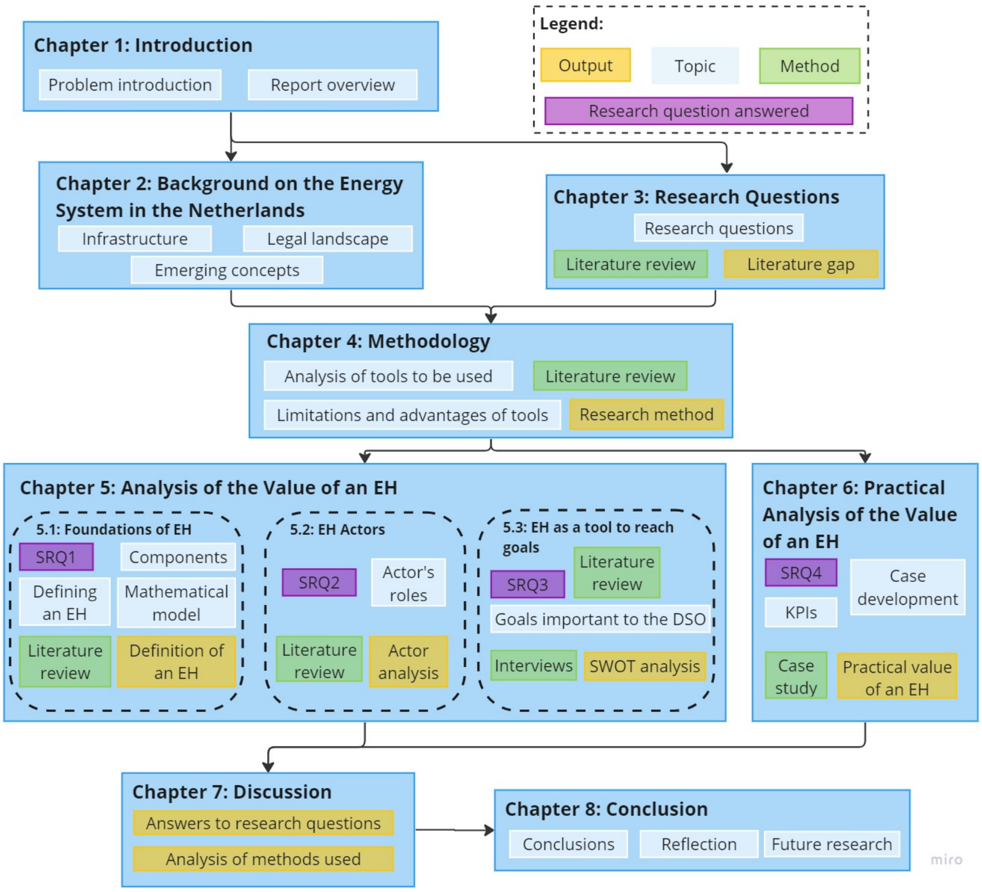

Figure 4.1: Research flow diagram

4.2. Data Gathering Methods

4.2.1. Literature Review

A literature review is conducted to provide a foundation of knowledge on energy hubs. Having a strong comprehension of the status of current developments in the area will facilitate theory development, subsequently promoting the advancement of knowledge in the field. This review also aims to contextualise the research conducted in this thesis through identifying a knowledge gap not previously covered. Literature review is also carried out throughout the thesis to provide necessary foundations when introducing new concepts.

The steps used to carry out the literature review are explained in this section. Initially various articles were read to contextualise the type of research currently available. These were selected from a basic 'Energy Hub' search on Google Scholar. From this primary research a further understanding of the common topics on energy hubs found in literature was grasped. Interesting literature cited within these articles was looked into and screened to see if they were relevant to be included in the literature review. This backward snowball approach of finding literature was repeated for different starting points. More refined searches to find other literature were made with more niche initial word searches as the work progressed. The following steps give more detail on the approach taken:

- **Step 1:** Use key word to find appropriate literature
- **Step 2:** Find relevant literature from the references
- **Step 3:** Log the literature that is applicable to the research in an organized spreadsheet
- **Step 4:** Find common topics in literature
- **Step 5:** Decide what topics make sense for this particular review
- **Step 6:** From these topics use more accurate key words in search
- **Step 7:** Find a knowledge gap in the literature

In order to find relevant literature, some screening criteria should be considered. Developments in technology, in policy and in the energy landscape are continuously happening, therefore it is important to select recent literature that tackles current issues. Moreover, looking at what journal the article is published helps understand its credibility.

4.2.2. Interviews

The approach used to conduct the interviews involved a structured gathering of firsthand information and insights from participants. The individuals selected to be interviewed possessed relevant knowledge and experiences related to the topic of energy hubs in the Netherlands.

The interviews had a very organised structure as they were conducted further along into the thesis, at a point where the topic was already well understood and the scope for the purpose of the interviews was well defined. Even though the interviews followed a structure, as seen in appendix A, it still left space for the participants to express their perspectives in a comprehensive manner.

Prior to conducting the interviews, ethical considerations were taken into account, including obtaining informed consent from participants. The interviews were all conducted through virtual platforms to provide the interviewees with more flexibility with their schedule. In order to be as transparent with the interviewee and ensure their comfort for a better cooperation, the interview template was completed with the screen share function. This meant that the participant could see and ensure that the transcription of what they were saying was either their exact words or highly representative of what they said, in the case that the sentence was not coherent. This allowed for any misunderstanding of what was said to be discussed on the spot, enriching the information gathered.

The methodology of interviews provided a rich and nuanced understanding of the research topic by capturing participants' perspectives, experiences, and expert knowledge. To ensure that all perspective and relevant knowledge was covered, all the interviewees were asked at the end of the interview if they recommend any further participants to be interviewed. By the end of the interview process all interviewees agreed that all the essential people at Stedin who are working with energy hubs were covered. A total of nine energy professionals were interviewed, covering different departments in Stedin, appendix B shows a list of the interviewees, and their role in Stedin. Only Stedin employees were selected as the SWOT analysis (that the interviews are used for) takes Stedin as the problem owner.

4.2.3. Data Provided by the Company

A significant method employed to gather information was through direct collaboration with the company itself. Stedin, as the focus of this study, provided various documents and shared project data, offering valuable insights into their operations, strategies, and perspectives.

Collaborating with the company allowed for access to internal reports, documents, and data that are not readily available in the public domain. This firsthand information provided a comprehensive understanding of Stedin's activities, initiatives, and decision-making processes. Moreover, obtaining information directly from the company ensured a high level of reliability and accuracy. The data and documents shared by Stedin are sourced directly from their operations and are therefore considered trustworthy and up-to-date.

Through the company's cooperation, specific project data related to energy hubs and grid operations were made available. This enabled a detailed analysis of real-world scenarios and facilitated a more comprehensive assessment of the benefits, challenges, and outcomes associated with energy hubs in Stedin's context. On top of that, engaging directly with the company, through informal meetings, allowed for a collaborative exchange of ideas, clarifications, and insights. This interaction facilitated a deeper understanding of the company's goals, challenges, and strategies, providing a nuanced perspective that might not be apparent through secondary research alone.

While the collaboration with the company provided valuable insights, the availability of data was subject to their discretion. Certain sensitive or proprietary information might have been withheld, limiting the scope of analysis. As the information was obtained directly from the company, there is a potential for inherent bias or limited perspective. Stedin's data and documents may reflect their own interests, priorities, and interpretations. It is important to acknowledge and critically evaluate this potential bias when analysing the information provided.

4.3. Data Analysis

4.3.1. Actor Analysis

In order to understand an individual's position in EHs it is important to know who are the other actors and how do they all interact. An analysis of each actor's interest and power in relation to energy hubs is performed using an power interest matrix. For this analysis, firstly a definition for "power" and "interest" must be established to then be able to apply these definitions to each actor and position them in the matrix. This analysis is done for a generalised EH case and also for two real-world case studies (ECUB and Reimerswaal) to have a better understanding of who needs to be closely managed, kept satisfied, kept informed, and monitored. This analysis is made to help answer sub-research question 2, and also to gain a deeper understanding into the interplay between the actors for the two case studies.

Performing such an analysis allows for the identification of the key stakeholders, which in turn helps prioritise stakeholders and allocate resources and attention accordingly. This information can be used to strategise stakeholder engagement through improving relationships, fostering cooperation, address possible conflicts, identify potential risks and others. On the other hand, the power-interest matrix is quite limited as it highly simplifies the actors through categorising them solely based on their power and interest towards EHs. It overlooks other characterisations, for example, their values, attitudes, and knowledge/expertise on the topic; these unexplored dimensions could give important further insight into the interplay of the actors. Moreover the power interest grid is a static representation, it does not represent how the power and interest of each actor may change in time (Pandi-Perumal et al., 2015).

4.3.2. SWOT Analysis

The SWOT (strengths, weaknesses, opportunities, and threats) analysis is a great technique for analysing how successful a tool can be in achieving a certain objective. Therefore, it is a great analysis to be used for the third research question. A SWOT analysis is performed to understand how successful an EH can be as a tool to reach certain ambitions important to the DSO. To determine individual objectives, a comprehensive approach is adopted, merging insights from literature review alongside data gathered from internal company consultations.

In order to analyse each goal, data is gathered through interviews. Moreover, the relevance of the goals selected is further validated by the interviewees. The interviews conducted, as described in section **??**, were designed to facilitate the SWOT analysis and followed a logical structure allowing for comprehensive information gathering specific to each goal. A SWOT analysis is conducted for each of these goals to understand the different advantages and disadvantages EHs bring, and in order to bring knowledge from different perspectives (e.g., technical, legal, innovative...) together. This can help facilitate cross-departmental collaboration, enhance the organisation, and may help identify interdependencies and challenges. For these SWOT analysis it is very important to analyse the EH concept particularly to the goal at hand and be specific about how it can be a tool to reach said goal. The following template is used to display the results of the SWOT analysis:

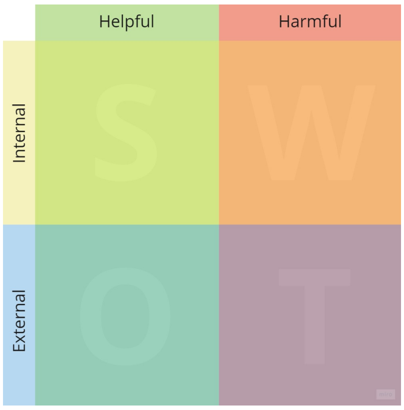

Figure 4.2: SWOT analysis template

4.3.3. Business Case

Analysing case studies and using real world information will help to gain a deeper understanding of the value gained through the implementation of an EH in a certain area. Moreover it gives tangible results allowing for a more interesting analysis of the value EHs bring.

A business case is formed for the Reimerswaal case study (an area with potential to become an energy hub). This aims to quantify the value brought by the implementation of an energy hub by comparing two different scenarios:

- **Business as Usual (BAU)** - This looks at a system that goes through the traditional procedure of increasing grid capacity, which is the expansion of the grid in the area with congestion management.
- **Base EH case** - This presents the configuration where an energy hub is introduced in the area.

To achieve a meaningful comparison between these two scenarios is the imperative to evaluate them against a uniform set of criteria. This calls for the establishment of well-defined performance indicators, which play a pivotal role in objectively quantifying and qualitatively assessing the outcomes of each scenario. Given that the core objective of the business case lies in unraveling how the identified advantages from the literature translate into real-world experiences, a methodical alignment with the same criteria is important.

To this end, an in-depth exploration of these criteria becomes not only a logical progression but an essential step to validate the relevance of theoretical insights in the practical realm. By conducting a meticulous analysis of the performance indicators within the context of each scenario, a comprehensive understanding of the degree to which the theoretical advantages materialise in real-life applications can be achieved. This structured approach ensures that the essence of the advantages observed in literature remains consistent with their observed effects in the practical setting, leading to informed and reliable conclusions.

5 | Analysis of the Value of an Energy Hub

This chapter analyses the value that EHs bring to the DSO. Initially it gives an understanding of what an energy hub is through exploring its fundamental qualities in section section 5.1. This is followed by an actor analysis in section 5.2, where the interests, roles and powers of each actor involved is investigated. Section 5.3 looks at how successful EHs can be as a tool to reach necessary goals of the DSO, giving insight into the future value of EHs.

5.1. Foundations of the Energy Hub Concept

It is first necessary to have strong foundations on the EH concept. This section first looks at the definition of energy hubs in section 5.1.1. This is followed by an understanding of the components that make up an energy hub, both physical and legal, in section 5.1.2. Finally, further detail on the EH concept and how it is modelled is given in section 5.1.3.

5.1.1. Defining an Energy Hub

This section looks into the definition of an energy hub. Since there is no set official definition, various academic literature sources are reviewed, and core components present in varying literature are used to formulate a definition. The methodology described in section 4.2.1 was used to find literature papers and to gather data on them. Table 5.1 list all the reviewed literature. The review also considers older literature to gain an understanding of how the concept of the energy hub was formulated and how it has evolved from then.

The EH concept was developed by a team at ETH Zurick at the Power Systems and High Voltage Laboratory and presented within the framework of the Vision of Future Energy Networks (VOFEN) project (Geidl, Koeppel, et al., 2006). This team had the aim to develop a vision for future energy systems that considered MES. They found that using the synergy between the different energy carriers can result in a more efficient energy system. Moreover, the study also concludes that the concept of EHs facilitates the movement towards non-hierarchical system structure and toward an energy system which is able to more easily integrate and interconnect different energy carriers.

Title	Reference	Publication Date
A Greenfield Aproach for Future Power Systems	Geidl, Klöckl, et al., 2006	January 2006
Energy Hubs for the Future	Geidl, Koeppel, et al., 2006	December 2006
Optimal Power Flow of Multiple Energy Carriers	Geidl and Andersson, 2007	February 2007
The Energy Hub - A Powerful Concept of the Future	Geidl et al., 2007	April 2007
Optimal Energy Flow of integrated energy systems with hydrogen economy considerations	Hajimiragha et al., 2007	August 2007
Multi-energy delivery infrastructures for the future	Kienzle et al., 2008	November 2008
Multiple-Energy Carriers: Modeling of Production, Delivery, and Consumption	Krause et al., 2011	November 2010
Energy Hub Based on Nuclear Energy and Hydrogen Energy Storage	Maniyali et al., 2013	May 2013
A Comprehensive model for self-scheduling an energy hub to supply cooling, heating and electrical demands of a building	Moghaddam et al., 2016	January 2016
Stochastic Scheduling of Integrated Energy Systems Considering Wind Power and Multienergy Loads Uncertainties	Chen et al., 2017	October 2017
Towards the next generation of smart grids: Semantic and holonic multi-agent management of distributed energy resources	Howell et al., 2017	September 2017
Energy hub: From a model to a concept – A review	Mohammadi et al., 2017	December 2017
Optimal bidding strategy for an energy hub in energy market	Davatgaran et al., 2018	April 2018
Optimal operation of energy hub in competitive electricity market considering uncertainties	Thang et al., 2018	May 2018
Capacity planning of energy hub in multi-carrier energy networks: a data-driven robust stochastic programming approach	Cao et al., 2020	October 2018
Standardized modelling and economic optimization of multi-carrier energy systems considering energy storage and demand response	Liu et al., 2019	February 2019
Modeling Carbon Emission Flow in Multiple Energy Systems	Cheng et al., 2019	July 2019
Modeling and Optimization of Energy Hubs: A Comprehensive Review	Maroufmashat et al., 2019	August 2019
The energy hub: An extensive survey on the state-of-the-art	Sadeghi et al., 2019	October 2019

Optimal operation of an energy hub considering the uncertainty associated with the power consumption of plug-in hybrid electric vehicles using information gap decision theory	Tafreshi et al., 2019	November 2019
Survey of Smart Grid Concepts and Technological Demonstrations Worldwide Emphasizing on the Oman Perspective	Al-Badi et al., 2020	January 2020
Distributed robust operational optimization of networked microgrids embedded interconnected energy hubs	Nikmehr, 2020	May 2020
Optimal Operation of Energy Hubs With Large-Scale Distributed Energy Resources for Distribution Network Congestion Management	Hu et al., 2021	March 2021
Multi carrier energy systems and energy hubs: Comprehensive review, survey and recommendations	Aljabery et al., 2021	July 2021
Optimal Operation of Residential Energy Hubs in Smart Grids	Bozchalui et al., 2021	October 2021
Compatibility about the concept of energy hub: a strict and visual review	Hammad et al., 2021	October 2021
Optimisation of a smart energy hub with integration of combined heat and power, demand side response and energy storage	Qi et al., 2021	November 2021
Safe reinforcement learning for real-time automatic control in a smart energy-hub	Qiu et al., 2022	March 2022
A comprehensive review on optimization challenges of smart energy hubs under uncertainty factors	Lasemi et al., 2022	May 2022
Distributionally Robust Optimal Bidding of Energy Hubs in the Joint Electricity and Carbon Market	Ma et al., 2022	May 2022
Optimal probabilistic operation of energy hub with various energy converters and electrical storage based on electricity, heat, natural gas, and biomass by proposing innovative uncertainty modeling methods	Tavakoli et al., 2022	July 2022

Table 5.1: List of literature reviewed continued

An energy hub lacks an official, universally accepted definition; rather, its interpretation varies among individuals. In essence an EH is a interconnected system of different energy carriers used to optimise their production, conditioning, storage and usage. The conceptualisation of an EH may vary depending on the specific vantage point adopted for analysis. The reviewed literature underscores the existence of diverse perspectives. To facilitate a comprehensive analysis, four distinct literary sources that encapsulate the prevalent viewpoints observed throughout the entirety of the literature review are selected. After evaluating the reviewed literature, these four have been thoughtfully selected for their ability to clearly present distinct viewpoints, ensuring a robust representation of each perspective. The references of the papers used, the key characteristics of their definitions of energy hubs, and the perspective they take are presented in table 5.2.

Reference	Characteristics	Perspective
Geidl, Koeppel, et al., 2006	A system interface between consumers, producers, storage devices and transmission devices in different ways: directly or via conversion equipment, handling one or several carriers.	Network of energy carriers
Howell et al., 2017	Compares EHs to polygeneration units, with the key differentiation that EHs are more elaborate and have a more complex internal arrangement of its components	Component of a system
Davatgaran et al., 2018	An EH is viewed as a prosumer in the energy market. Therefore, may also be considered a price-taker.	Actor in the energy market
Qiu et al., 2022	A node with input variables that are optimally conditioned, stored and dispatched, with the goal to lower energy costs	Mathematical model

Table 5.2: Varying characteristics of energy hubs from different literature and their associated perspectives

When combining all these perspectives, some criteria must be met for these characteristics to be satisfied. The identified **limiting criteria** are:

- Must have multiple energy carriers that are converted within the system - this criteria ensures that there is more than one energy carriers involved in the system, moreover the necessity of having conversion within the system ensures that the energy carriers are connected for their optimal utilisation.
- Must follow an optimisation strategy which leads to an increased efficient usage of the system components - the energy hub must be operated in a way that the components are used efficiently.
- All components are physically connected - the components must be all connected to each other via cables or pipelines.
- There must be collaboration between the individual actors - the actors involved in the energy hub must communicate and collaborate in a way that an agreed upon optimum can be reached.
- An EH operator must manage the system - there needs to be efficient management of the system to ensure all the other criteria are met.

Even though there are characteristics that should be common to all EHs (and therefore make up the definition of an energy hub), there are also control variables that will differentiate between the different types of EHs resulting in different types of EHs. Since it is a relatively new concept, there are no official classifications for energy hubs, however the following **control variables** allow for a differentiation between different types of EHs:

- Storage ability - an EH may not have a storage component or it may have multiple, or even different types of components.
- Types of components - types of input, converter, storage, and output components may vary depending on the energy supply and demand in the area.
- Size - EHs can range from small sizes at a component level (micro-EH) to large industrial clusters (macro-EH).
- Complexity of optimisation function - changing complexity can be done by making the system smart, through the automation of decision making (Bozchalui et al., 2021) or through introducing scheduling.
- Involvement in the energy market - the EH can decide to participate in the energy market and optimise its strategy for bidding in the energy market.
- Location - an EH is not limited by a particular location.

Mart van Bracht (van Bracht, 2021) identifies different possible classifications of energy hubs that may become prevalent in the Dutch energy system. These classifications of energy hubs all have different control variables in them as they have different purposes. This shows how the concept can be used in different contexts, however all still have the limiting criteria previously mentioned. These classifications include: offshore EH, industrial EH, EH at an interface with a rural area, and mobility EH.

From the above mentioned criteria and the defined control variables, an overall definition is made:

An energy hub is any system with multiple energy carriers as inputs that are being conditioned and dispatched to fulfil a pre-determined optimisation goal within a geographically limited area. The function of this goal will vary in complexity depending on the size of the hub, the number and type of components, and the level of storage ability. The EH system has various stakeholders who are governed by an entity responsible for its operation, and may participate in both from a supply and demand energy market.

5.1.2. Components

This section reviews components that make up an energy hub to gain a deeper understanding of how EHs function. The components of an energy hub refers not only to the physical or technical components (in section 5.1.2) but also to the legal and market mechanisms put in place, found in section 5.1.2.

Physical Components

The types of components and how they are arranged will vary depending on the classification of the EH. There is no one component that must be present for the system to be considered an EH, however there are some components more commonly used than others. Mohammadi et al., 2017 review what components were mostly found in literature up until 2017. This is a less recent paper, however the purpose is to understand what are the possible system components as opposed to new concepts that highly change over time.

1. **Inputs** of an EH can be any energy carrier being inputted into the system, there are

no restrictions to what these may be. However, as EHs aim to be a tool to help modernise energy systems, inputs tend to increasingly be energy sources that are wished in a future energy system (i.e. away from traditional, more polluting sources, and towards cleaner, more sustainable sources). The inputs for EH models found in literature by Mohammadi et al., 2017, in order of most commonly found, are: the electricity grid, the natural gas network, solar energy, wind power, district heating, biomass, hydropower, water and nuclear energy. An overwhelming majority of the models (>98%) include both the electricity network and the gas network as inputs, compared to the next input in the list (solar energy) with only just above 19% of considered literature using it as an input. This shows the predominant need of the distribution grids as inputs for EHs, therefore their importance for grid operators. The electricity grid in itself is not a component of the energy hub, when referring to the electricity grid (or the gas grid) as an input, the component that is part of the energy hub is the connection point to the grid.

2. **Converters** used in EHs will vary depending on the inputs and outputs. The conversion technologies mostly found in literature (as per Mohammadi et al., 2017) are: combined heat and power (CHP), gas boilers, transformers, absorption chillers, heat exchangers, electrolysers, fuel cells, electrical chillers, heat pumps, biomass boilers and compressors.
3. **Storage devices** are not an essential part of an EH, however can highly increase system flexibility, therefore allowing for a more optimal dispatch of the outputs. The storage devices that may be added to an EH are dependent on the types of output and can be: electrical storage, thermal storage, hydrogen storage, ect.
4. **Outputs** of an EH will depend on the type demand that needs to be satisfied. Usually the EH model will be designed accounting for the required output profile. Common outputs found in literature include electricity, heating, cooling, hydrogen, natural gas and compressed air (Mohammadi et al., 2017).

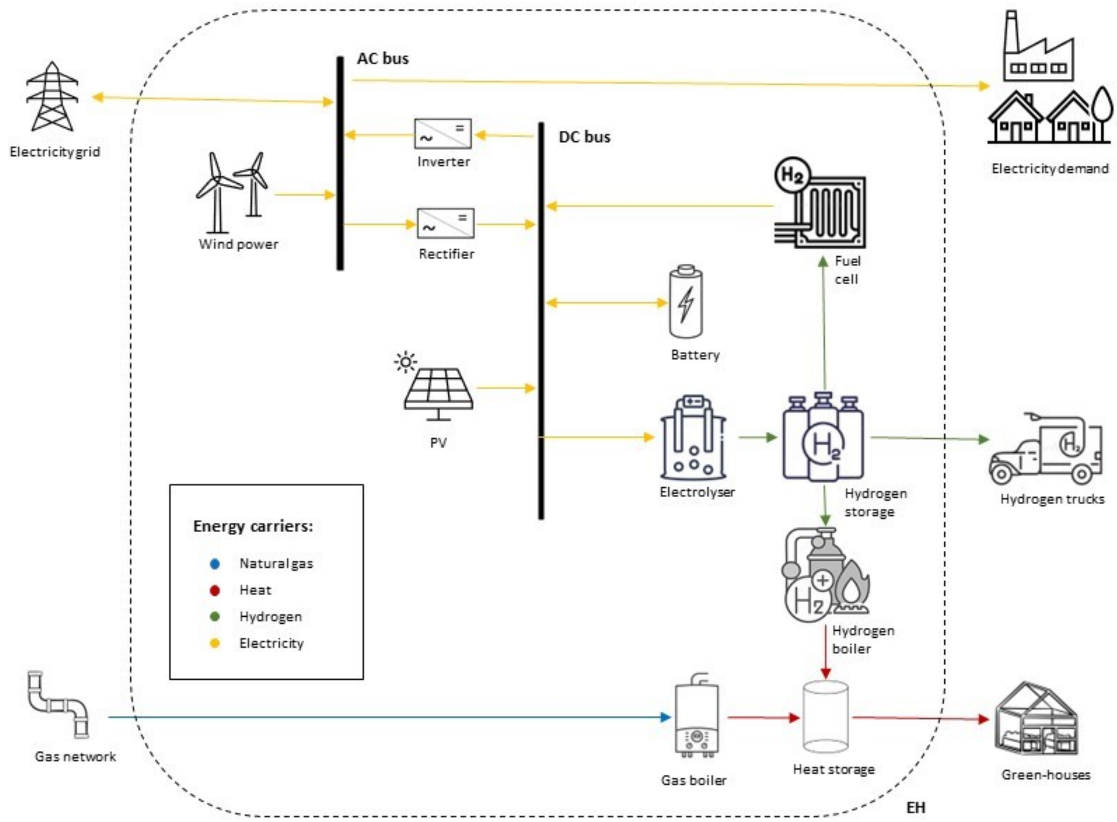

Figure 5.1: Diagram of a potential configuration of an energy hub showing different components and how they are connected

Figure 5.1 shows a diagram with some of the components most commonly found is literature (as per Mohammadi et al., 2017). This is a hypothetical energy hub with the purpose to show a possible interplay between the different system components and to better visualise how this can behave. The different colored arrows shows what energy carrier is being transported. This EH includes a connection to the electricity and gas grid, solar energy (PV - photovoltaic), and wind power generation as the system component inputs. The diagram clearly shows that the electricity and gas networks are not part of the energy hub, but rather the connections to them are.

This system contains various converters: inverter, rectifier, fuel cell, electrolyser, hydrogen boiler and gas boiler. The inverter and rectifier convert energy from DC (direct current) to AC (alternating current) and vice versa; these types of converters do not change the energy carrier, therefore a system with only these (and no other converter types) would not be an energy hub. The other converters bring different energy carriers into play and allow for the switch between them. The electrolyser converts electricity into hydrogen, the fuel cell converts hydrogen into electricity, and the hydrogen and gas boiler convert hydrogen and gas into heat, respectively.

This system also shows some storage components, with a battery representing a short term electricity storage component. The hydrogen storage can be considered a more long term electricity storage component, as the fuel cell then is able to convert the hydrogen back into electricity, however it also plays a role in storing hydrogen that will later be converted into heat. Having the ability to store these energy carriers adds more flexibility into the system as their dispatch can now be further optimised and less reliant on uncontrollable constraints (e.g., weather dependent DERs). On the other hand it brings further the system losses, e.g., with the electrolyser and fuel cell. Even though their efficiencies are improving they are still not very efficient. An 80% electrolyser efficiency was reported by Hysata's capillary technology (IEA, 2022), and efficiencies up to 60% for fuel cells (U.S. Department of Energy, 2015), even though these are improving the energy loss is still significant. Here part of the optimisation considerations should be to only use these components when it fits the EH's strategy (e.g., if the strategy is to lower energy prices then the electrolyser should be on at times when the energy price is low and the fuel cell should be used when prices are high). The heat storage also brings extra flexibility.

This system assumes an electrical demand, a hydrogen demand, and a heat demand as its system outputs. The purposes of these outputs were inspired by van Bracht, 2021 EH classifications, them being industrial or residential electrical demand, hydrogen for mobility, and heat for green houses (needed in rural areas). This is a hypothetical energy hub, all these different types of demands might not be found in the same EH, however this system shows how different components can interact to fulfill a certain demand.

All these components should be optimally modelled, section 5.1.3 goes into further detail about the considerations to be taken into account when modelling an optimisation strategy of an EH.

Legal and Market Components

An energy hub can either be connected to the central energy system (the electricity grid and the gas grid) or have its own closed distribution system (CDS). In the case that it the energy hub is assembled within a CDS, then the necessary approvals are needed, more information on this can be found in section 2.3.3. Since the interest lies withing grid connected energy hubs, no more detail on the configuration within a CDS is given.

The EH concept is presently in the early stages of development, with the majority of EH-related projects either in pilot stages or in their initial phases, therefore there is no set out legal framework or procedure to be taken. The concept is expected to evolve, with more defined procedures. Energy hubs do not have defined legal steps to be taken, as the concept is not recognised under Dutch law. There is no legal procedure for a system to become an energy hub, however, there are contracts that can be used depending on the structure design of the energy hub. Currently the Dutch grid operators are preparing a position paper on a group ATO, which aims to facilitate the maturing of energy hubs through recognising a group of individuals as one connection (Stedin, personal communications).Other contracts that may be used are developed in a need basis as different projects surface; these can then be reused in similar future projects.

Different legal requirements have to be considered when forming an EH. The connection to the grid is important and can be done in different ways. Currently some projects are exploring a balancing contract; in this case the individuals that partake in the EH maintain their individual connections to the grid, and all together act as a collective that has a contract with the DSO. This contract ensures the aggregated capacity does not go above a set limit, and if it does, an agreed upon penalty must be payed, it should also include technical agreements where the coordination, monitoring and metering is established. This approach is taken in Lage Weide, a pilot project termed energy hub that is further explored in chapter 6. Another procedure to securing a grid connection is through a group ATO, as aforementioned this is currently being developed, but in the future can play a significant role in facilitating the advancement in EHs.

An agreement between the participants of the EH is also needed, clearly establishing rules agreed upon by everyone involved. What is agreed on changes depending on the project, but common things that should be agreed on are, compensations, energy demand, energy supply, who has priority, penalties, etc... This agreement should be managed by the EH operator, a position agreed upon by all the players, to ensure everyone sticks to their requirements. These advised requirements are suggested in order for the hub to stick to its contract, are are currently being investigated in Stedin (Stedin, personal communications).

5.1.3. Modelling an Energy Hub

This section further reviews the perspective of a mathematical model to show the operating principles behind the optimisation of an EH. It looks at an EH as an optimisation problem, highlighting possible objectives, degrees of freedom, constraints, and uncertainties. The modelling of EHs is very common in literature (evident from the titles of the reviewed literature in table 5.1), therefore the literature review is also applied in this section.

From a mathematical perspective, an EH is a system containing various inputs which undergo an optimisation function to produced desired levels of outputs (Qiu et al., 2022). This theoretical model is illustrated in figure 5.2, and shows the inputs (P_{1-n}), being conditioned through converters, transmitters and storage components, to produce outputs (P_{L1-Ln}).

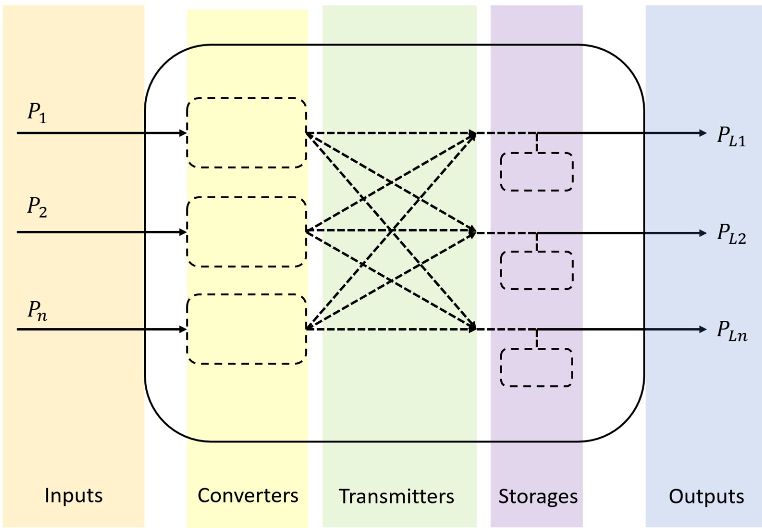

Figure 5.2: Theoretical model of an EH (adapted from Thang et al., 2018)

A matrix-vector mathematical model of the theoretical model presented above (figure 5.2) is shown in equation 5.1. The equation depicts how optimised outputs (P_{L1-Ln}) can be derived through conditioning input energy carriers (P_{1-m}) through a coupling matrix, with the different matrix elements representing coefficients of features of the EH (Mohammadi et al., 2017). The amount of coefficients and their units highly depend on the structure of the EH, therefore a generic representation is shown. Having this mathematical representation be a generic framework allows for an unconstrained, flexible model of any system with no needed assumptions in the system size (Maroufmashat et al., 2019).

$$\begin{bmatrix} P_{L1} \\ P_{L2} \\ \vdots \\ P_{Ln} \end{bmatrix} = \begin{bmatrix} c_{11} & c_{12} & \dots & c_{1m} \\ c_{21} & c_{22} & \dots & c_{2m} \\ \vdots & \vdots & \ddots & \vdots \\ c_{n1} & c_{n2} & \dots & c_{nm} \end{bmatrix} \cdot \begin{bmatrix} P_1 \\ P_2 \\ \vdots \\ P_m \end{bmatrix} \tag{5.1}$$

The theoretical model can also be translated into a mathematical optimisation problem. The optimisation problem varies depending on the energy hub, however is widely accepted as a multi-integer optimisation problem across various literature (Davatgaran et al., 2018; Lasemi et al., 2022; Moghaddam et al., 2016). For an optimisation problem to be considered multi-integer, it must have non-linear constraints, this is the case for an EH as it has to consider the ramping-up and ramping-down of various system components. Davatgaran et al., 2018 consider this optimisation problem as a mixed integer linear programming (MILP) problem. Whereas, Moghaddam et al., 2016 propose a mixed integer non-linear programming (MINLP) to produce a model for self-scheduling energy hubs. The optimisation problem will vary depending on the parameters attributed to the considered EH, therefore various possible goals, degrees of freedom, constraints and uncertainties are identified.

Objectives

The **objective** of an EH is to increase the efficiency of use of the different system components (Qiu et al., 2022). This aims to reach different goals (depending on the energy hub), including, decreasing energy prices, maximising the introduction of renewable energy, and making the most use of the existing space and resources, amongst other goals. To reach the optimisation of a hub, the aggregation of smaller objectives done to optimise the conversion, transmission and storage of the different energy carriers. Such objectives include:

- Optimal energy exchange between equipment - reduced transmission losses (Maroufmashat et al., 2019)
- Optimal energy exchange with transmission and/or distribution systems (Tavakoli et al., 2022).
- Optimal charge and discharge for battery systems (Davatgaran et al., 2018; Moghaddam et al., 2016)
- Optimal bids to submit to day-ahead market (Davatgaran et al., 2018)
- Optimal scheduling of the dispatch of outputs (Qiu et al., 2022)

New studies also start considering carbon emissions and the carbon market into their modelling. Cheng et al., 2019 present a method for calculating carbon emission flows in MES. The ability to calculate carbon emission flows for the power network, gas network and heating network of an EH means that these levels may also be optimised through changing the optimisation function to also include a reduction in carbon emissions as its objective and therefore competitively bid in the carbon market too (Ma et al., 2022).

Degrees of Freedom

Degrees of freedom refer to the optimisation variables, these are parameters that can be changed to fulfill the optimisation function. For an EH model these include:

- Generation of power, heat, chemical compounds
- Storage of energy, heat, cold, chemical compounds
- Possibly demand if demand response is considered e.g. by Davatgaran et al., 2018.

Constraints

The optimisation variables are restricted by **constraints** inherent to the system components. These differ depending on the components present, some examples of possible constraints are:

- Power generation - in the case of weather dependent DERs, this is influenced by the weather forecast. This can also be influenced by the location and how much land is available to be used for a particular purpose.
- (Multi-energy) power balance and (multi-energy) power flow inside the EH (Davatgaran et al., 2018)
- Capacity limitations of converters (Davatgaran et al., 2018)
- Ramp-up/down time pf generating unit
- State of charge (SOC) and capacity of storage systems
- Efficiency of elements
- Demand can be considered a constraint, however if the system uses demand response then it is considered a degree of freedom, as seen before.

Uncertainties

After the introduction of the EH concept by Geidl, Koeppel, et al., 2006, further studies have been made testing and improving on the concept. Currently research in the EH concept is increasingly looking at modelling the inherent **uncertainty** associated with EHs through stochastic and robust optimisation strategies (Lasemi et al., 2022; Moghaddam et al., 2016), in order to use them for the smart scheduling operation of an EH (Qi et al., 2021; Qiu et al., 2022). These studies consider further constrains and optimisation variables intrinsic of a changing energy network including, demand side response, energy storage, and using smart control.

Moreover, there has been an increase interest in understanding how an energy hub can act as an energy market player through understanding what an EH's bidding strategy should be. Davatgaran et al., 2018 study this by taking a stochastic approach to their optimisation model looking into the uncertainty in the day-ahead market prices, real-time market prices, and in the generation of a wind energy. Tavakoli et al., 2022 model a stochastic framework to consider uncertainties in solar irradiation, wind speeds and day-ahead energy markets through the generation of random scenarios based on real historical data in Finland. This modelling is used to generate an optimal operational strategy to increase financial gain from energy market prices.

5.2. Energy Hub Actors in the Netherlands

This section delves into the key actors engaged within the context of an energy hub. The initial segment, designated as section 5.2.1, provides an introduction to these pivotal actors, laying the foundation for a comprehensive understanding. Subsequently, in section 5.2.2, an in-depth assessment is conducted, focusing on the dynamics of power and the underlying interests that drive these actors.

5.2.1. Mapping of Actors in an Energy Hub

An important defining criteria for energy hubs is that there are various stakeholders acting as a group. This can be quite complex, therefore it is important to initially understand who are the actors involved in EHs, and how these actors are connected. These actors in the Dutch energy system are grouped and shown in figure 5.3:

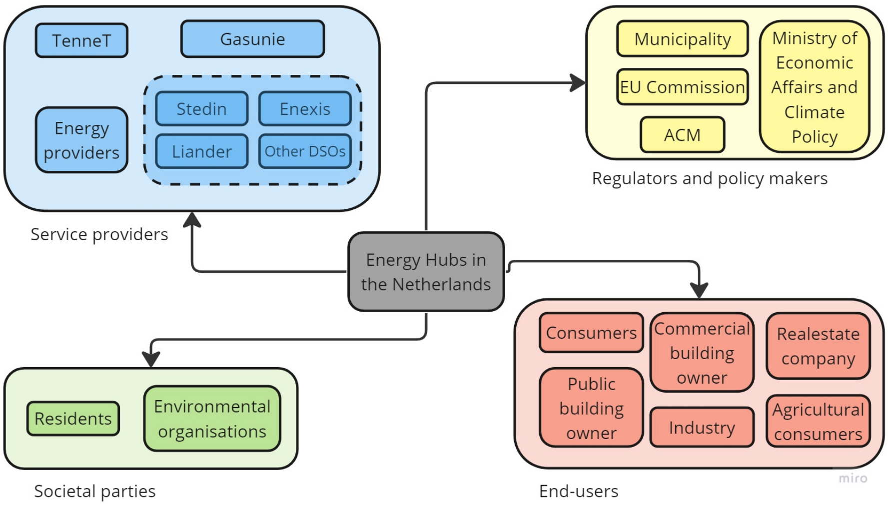

Figure 5.3: Stakeholder map for EHs in the Netherlands (adapted from Sepponen and Heimonen, 2016)

Figure 5.3 adapts information gathered from Sepponen and Heimonen, 2016. It allows for a visualisation of the different actors involved with an energy hub, and how they may be grouped.

The term ”service providers” pertains to entities engaged in furnishing services, encompassing those catering to the operational aspects of the energy system, as well as those contributing to the provisioning of energy itself. Notably, Transmission System Operators (TSOs) such as TenneT and Gasunie, alongside Distribution System Operators (DSOs), function as system overseers, with their roles described in chapter 2. Meanwhile, ”energy providers” encompasses companies that supply energy to the system at large.

Chapter 2 provides insights into certain regulators and policy makers. It is noteworthy that the depth of knowledge possessed by the governing entity tends to increase as the scope of their regulatory jurisdiction narrows. Consequently, in the Netherlands, local decision-making is done by the municipalities. Municipalities are the primary facilitators for local energy transition (Beauchampet & Walsh, 2021). They have a large say on the adoption of environmental policies within their locality, they have the autonomous power to decide on the best solution for their area (Government of the Netherlands, 2023a). Roles and interest of municipalities vary quite significantly depending on the municipality and their goals. They are very knowledgeable about local needs and easily approachable by the citizens, making them vital in the promotion and realisation of energy transition in the area (Warbroek & Hoppe, 2017).

Societal parties, including residents and environmental organisations, are stakeholders that embody a societal presence and hold significant influence in the context of energy hubs. Their roles extend beyond conventional economic or institutional interests, encompassing broader concerns related to social well-being, environmental sustainability, and community development. In essence, these societal parties transcend economic considerations and contribute to a more holistic evaluation of energy hub projects.

End-users refers to parties who use the outputs produced by the energy hub. Figure 5.3 gives examples of possible end-users including industry, commercial building, agriculture and others. It is important to understand the end user as these will have a different role and different amounts and types of energy demands that must be satisfied.

5.2.2. Power and Interest Analysis of Actors in an Energy Hub

This section places the actors in a power-interest grid, in order to understand and visualise the positioning of each actor. The section initially delves into the definitions of the terms ”power” and ”interest”. These definitions are then used to place the actors in a power interest grid.

When placing stakeholders in a power-interest grid, it is important to initially define the terms ”power” and ”interest”. Power, in the context of a power-interest grid for stakeholder analysis, is defined as the ability of stakeholder to exercise their influence to achieve desirable outcomes (Guðlaugsson et al., 2020). This refers to the stakeholder’s ability to influence decisions, actions, and outcomes within the energy hub. Therefore for this study the term ”power” is defined as: *”the power of an actor to influence the development of an individual energy hub”*. Whereas the term ”interest” depicts the impact experienced by the stakeholder (Guðlaugsson et al., 2020), moreover it looks at the stakeholder’s level of concern, engagement, or investment in the activities and outcomes. For this study is defined as *”the impact experienced through the development of the individual energy hub”*.

Placing stakeholders on the grid involves assessing the definitions of power and interest for each stakeholder and positioning them accordingly. Stakeholders with high power and high interest typically fall into the ”Manage Closely” category, as they hold significant sway and investment. Those with high power and low interest might belong to the ”Keep Satisfied” category, as they can influence decisions but may not be closely involved. Stakeholders with low power and high interest could be placed in the ”Keep Informed” category, as their input is important but their ability to influence is limited. Finally, stakeholders with low power and low interest might fit the ”Monitor” category, as they have less impact on the hub’s outcomes. Various actors have interest in EHs in the Netherlands as this can directly affect them. These actors are further analysed in figure 5.4, where a comparison between their interest and the power they have towards EHs is evaluated. This is a generalised analysis, and can differ from project to project, however it looks at the development of an individual energy hub and not at the concept overall. For example, the Ministry of Economic Affairs has high interest in EHs as a tool to reach certain national goals, however not as much interest in EHs at an individual level, this interest is passed down to more local authorities, i.e., municipalities.

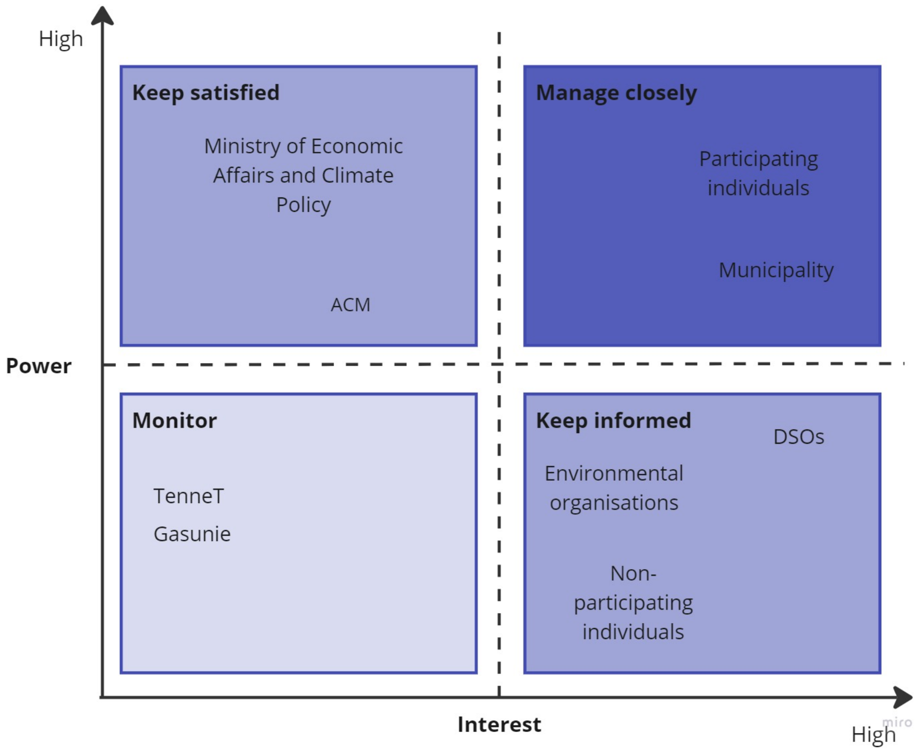

Figure 5.4: Generalised power-interest grid for the stakeholders involved in an individual energy hub

Figure 5.4 positions actors in different quadrants of the power-interest grid using the definitions for power and interest for this situation. The reasoning for each positioning is provided:

Participating individuals: These are actors that make up the energy hub, from figure 5.3 these may be for example the end-users or energy providers. The interests and roles these play differ depending on who it is, their previous position and their future plans. They have high power and interest as their actions have high influence on the development of the energy hub.

- **New entry:** This refers to individuals who have not yet secured a grid connection. These actors are likely to have high interest in collaborating with other actors in the area as it could result in a faster realisation of their project.
- **Existing connection:** The interest of actors who already have a connection is more variable. Since these actors already have a safe, secure and reliable way of dispatching or receiving their electricity they have less incentive to participate. However, it may still be advantageous depending on the actor. They may want to change their business practices and include other type of energy carriers, they may also want to increase their connection for various reasons. Therefore these actors still have a high interest in the EH, and a lot of power as they are the ones with a connection to the grid, accordingly have more negotiation power.

Municipality: Since municipalities are the primary facilitators, they have high power in the development of an energy hub. They make decisions in the environmental policies within their locality, giving them a lot of power as such policies may directly affect energy hubs, either making it more difficult or facilitating the implementation of energy hubs. They also have high interest as they are knowledgeable about local needs.

ACM: The ACM is the dutch energy regulator, responsible for the independent supervision of the energy market, meaning they have a lot of power in facilitating the deployment of energy hubs through policy. However, they do not have high interest of energy hubs at an individual basis, therefore are placed in the keep satisfied quadrant.

DSO: DSOs have high interest because energy hubs have the potential to make the system more efficient highly impacting the DSOs' functions. Due to their obligation of connecting everyone in a non-discriminatory fashion they are limited to their legal responsibilities. This lowers the DSOs' powers as they may not make decisions to favor or disfavor energy hubs.

Non-participating individuals: These are individuals that are within the same geographical area however are not part of the actors in the energy hub, for example residents of the area, as shown in the stakeholder map in figure 5.3. They have high interest as they may be highly impacted by the introduction of an energy hub, for example, the energy prices in the area may change affecting their finances. An additional interest may be how the energy hub will affect the energy landscape in the area, as it may result in higher or lower connection capacity to the electricity grid, This can change the individuals' future energy plans in the area.

Environmental organisations: These type of organizations' priority is to ensure practices that do not harm the environment. In the case of energy hubs, as these are a new concept emerging from a changing energy landscape, they tend to incorporate renewable energy and green technology making them of interest to environmental organisations.

Ministry of Economic Affairs and Climate Change: The Ministry of Economic Affairs and Climate Change (often referred to as the Minister) is in charge of making a strong entrepreneurial business climate through ensuring the right conditions that will allow room for growth and innovation (Government of the Netherlands, n.d.). The minister does this through implementing policies that encourage the sustainable development of the energy system. Therefore it has high power, however at an individual energy hub level it has low interest.

Gasunie: Gasunie is the operator and manager of large-scale gas infrastructure of the Netherlands. It is in a position of low interest and low power as EHs are usually at a distribution scale, therefore the interest will lie with the distribution operator instead.

TenneT: TenneT is the transmission system operator (TSO) of the Dutch electricity grid, EHs tend to happen at a distribution level, therefore TenneT does not have much interest. There may be cases where TenneT will have more interest and power over an EH if this is to be connected with the higher voltage grid, which they operate.

5.3. Energy Hub as a Tool to Achieve Goals Important to the DSO

It is not only important to analyse the value that EHs currently bring, and the problems that it can currently solve, it is also important to take a step forward and analyse their position in a future energy system. This section analyses the value energy hubs can bring in the future through analysing how successful they are in achieving certain goals and ambitions important for DSOs. Section 5.3.1 identifies which goals are important in this context, this is followed by a SWOT analysis of each goal in sections 5.3.2, 5.3.3, and 5.3.4. The analysis uses information gathered through interviews, a document made with information from all the interviews can be found in appendix C.

5.3.1. Goals Important to DSOs

This section determines which goals are important for the Dutch DSOs (with a particular focus on Stedin) in the context of analysing the value of energy hubs.

The goals were carefully narrowed down through a structured process that drew from Stedin's operational obligations and visionary objectives. DSOs have the obligation set out by law to connect all requests (TenneT, 2023). From this obligation the first goal is established: "Connect all requests to the grid". In order to consider not only Stedin's (and other DSO's) obligations but also their future visions, further analysis is made into Stedin's ambitions. In Stedin's vision and strategy (Stedin, n.d.), three key focus point are highlighted on Stedin's vision for future grid management. These focus points are:

- Better grid management
- Facilitating the energy transition
- Sustainable business operations

The first two points are reasoned into goals to be analysed in this section. Since the last point relates to Stedin's business operation, it is not relevant in this context of analysing the value of energy hubs. By engaging in discussions with experts to refine the articulation of these strategies in a manner tailored to the current analysis, the following goals have been derived:

- Make better use of existing infrastructure
- Increase the share of renewable energy (in the dutch energy system)

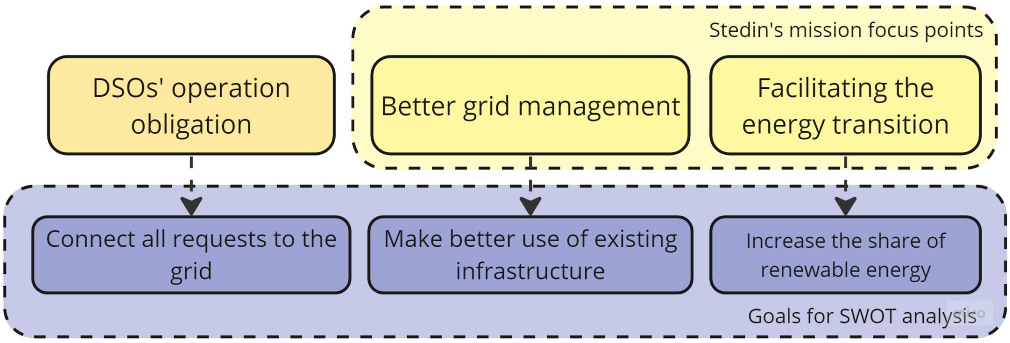

Figure 5.5: Formulation of goals important to Stedin (and other DSOs)

Figure 5.5 shows a visualisation of how the three goals have been developed considering both Stedin's obligations and vision and strategy. Further detail on the importance of each goal is given below:

1. **Connect all requests to the grid** - this is an ambition that Stedin and other DSOs have as part of their operation. Currently, due to congestion, not all connection requests can be realised and they enter a waiting list until there is enough capacity in the grid. Therefore tackling this issue is very important to ensure everyone has unrestricted access to the energy system.
2. **Make better use of existing infrastructure** - expanding the grid is a very costly endeavour, which will cost TenneT a predicted 111 billion euros in the coming decade (Kyllmann, 2023). A better use of the existing infrastructure will result in a reduced necessity to expand and therefore save money. Since the DSOs' budget is obtained through tariffs from those who have a grid connection, it is important to keep these as small as possible.
3. **Increase the share of renewable energy (in the dutch energy system)** - increasing renewable energy is becoming increasingly important, this is backed by The Energy Agenda which sets out a road-map to 2050 with almost 100% of energy being renewable (Government of the Netherlands, 2023b).

The analysis of these goals will provide valuable insights for Stedin and other DSOs to navigate the evolving energy landscape, improve grid operations, and support the transition towards a sustainable and renewable energy future. A SWOT analysis is conducted for each of these goals, looking at what are the strengths, weaknesses, opportunities and threats that energy hubs pose in reaching each goal. Interviews with Stedin employees were conducted as a data gathering method. The interviewees selected are from various departments providing the analysis different perspectives and expertise (a list of the interviewees and their roles in the company is provided in appendix B). Further information about the interview process is given in section 4.2.2 of the methodology chapter.

5.3.2. Goal 1: Connect all requests to the grid

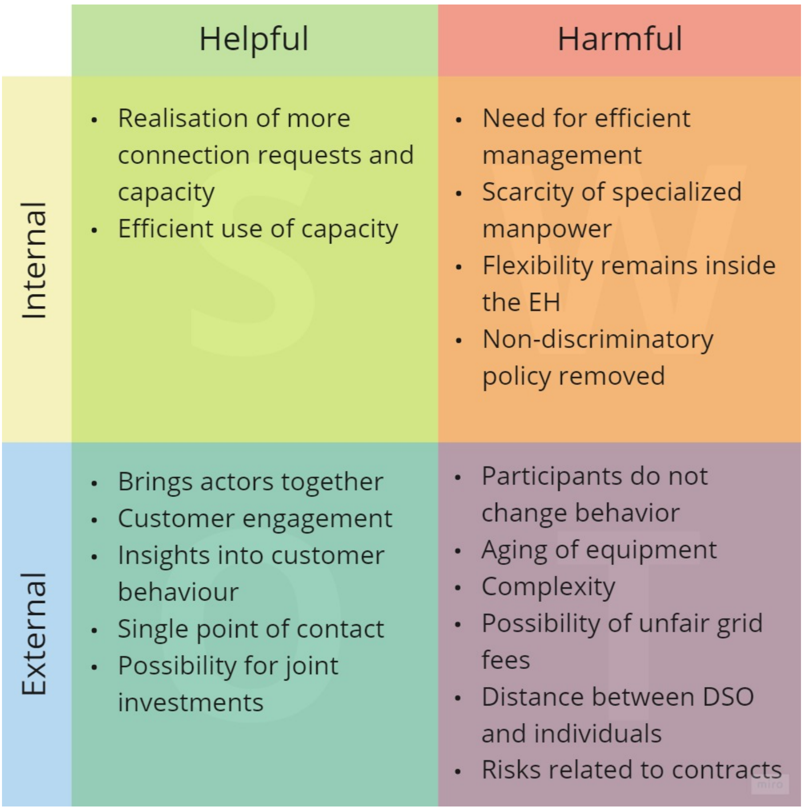

Figure 5.6: SWOT analysis for goal 1

There are only two **strengths** highlighted in this analysis as most of the interviewees had similar views for this goal. There is a big consensus between a majority of the interviewees that EHs are helpful in realising more connection requests or capacity for already existing players. Theoretically, the introduction of EHs enables more efficient utilisation of capacity, subsequently unlocking additional capacity. Furthermore, some interviewees even go on to say that this objective is what is presently fueling the increasing interest towards EHs, emphasising the driving force behind its increasing popularity.

On the other hand, several **weaknesses** have been identified. Efficient management of the energy hub emerges as a critical necessity to ensure optimal performance and avoid operational inefficiencies, this is highlighted as a weakness as this requires specialised knowledge and competence. The scarcity of specialised manpower, mentioned by interviewees with different backgrounds, backs up the previous point as it poses as a significant challenge in effectively operating and maintaining these complex systems. Furthermore, there is the concern regarding the limited control over components within the energy hub, which has the potential to impact the overall stability of the grid. Similarly, another interviewee emphasises that while energy hubs offer flexibility, this flexibility remains confined within the boundaries of the hub itself, potentially limiting the broader scope of benefits for players outside the EH. Another weakness is that energy hubs are not necessarily bound by non-discriminatory policies, potentially leading to inequitable access and treatment, this is a characteristic prominent in the DSO's current role, as explored in section 2.2. Moreover, concerns are raised about the capacity of energy hubs to handle *all* requests, suggesting that they may not be able to cope with the increasing demands effectively and the realisation of connection requests and capacity is limited.

Several **opportunities** have also been identified. Firstly, energy hubs bring together various stakeholders, fostering collaboration and coordination among key players in the industry. This collaborative approach opens avenues for collective problem-solving and promotes synergistic outcomes. Moreover, customer engagement emerges as a valuable opportunity; energy hubs provide an incentive for customers to gain further perspective into their consumption patterns, therefore making them more conscious of their energy needs and how these can be increasingly met with innovative solutions. This also provides the DSO with valuable insights into customer behavior; by analysing data and patterns of the individuals' participating in the EH, the DSO is able to gain a deeper understanding of customer needs, consumption patterns, and future energy requirements, thereby enabling informed decision-making and more effective grid planning. Moreover, the opportunity for a single point of contact through energy hubs, makes communications more effective and simplifying interactions between the DSO and its customers. Furthermore, energy hubs offer the potential for joint investments, this potential for collaborative ventures can drive innovation through shared economic benefits. These opportunities position energy hubs as catalysts for transformation within the energy sector, paving the path towards customer-focused strategies, improved planning capabilities, and collaborative collective action.

Utilising energy hubs to connect an increasing number of requests to the grid presents a range of potential **threats**. The risk of participants not changing their behavior is highlighted, hindering the achievement of desired efficiency gains. This can also have effects on players outside of the EH, leading to apprehensions about the potential for unfair grid fees, which in turn leads to an uneven distribution of cost burdens among participants. There are also concerns of equipment aging; posing a long-term threat to the reliability and sustainability of energy hubs, moreover may lead to further maintenance needs. Moreover, the complexity inherent to the operation of EH is a threat as their effective organisation and management of intricate operations is needed. The challenges stemming from the distance between the DSO and individuals potentially impede effective communication, understanding, and responsiveness. Interestingly, this observation contradicts the opportunity presented by having a single point of contact, illustrating how the impact of this issue varies from case to case. Concerns about the possibility of parties discontinuing their cooperation are expressed, which could disrupt the functioning and viability of energy hubs. Additionally, ensuring contractual obligations are upheld by all entities involved can be difficult, introducing uncertainties and undermining the stability of energy hubs. Addressing these threats requires careful consideration and the implementation of proactive mitigation strategies to tackle behavioral challenges, ensure infrastructure resilience, increase coordination, promote fairness in fee structures, bridge communication gaps, foster collaboration, and enforce contract compliance within the energy hub context.

5.3.3. Goal 2: Make better use of existing infrastructure

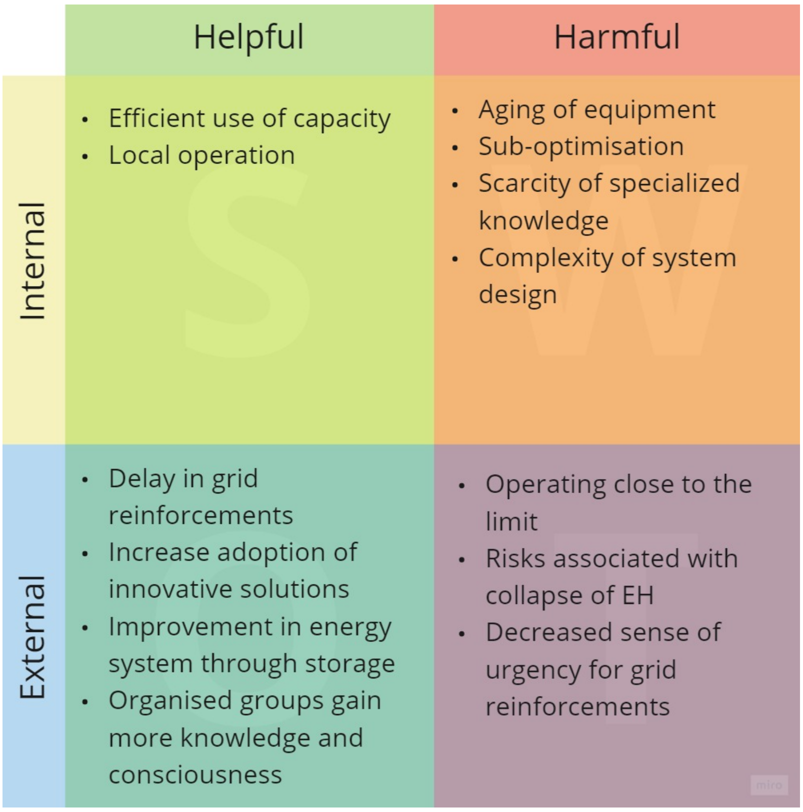

Figure 5.7: SWOT analysis for goal 2

Efficient use of capacity emerges as a notable **strength**, as highlighted by most interviewees. This approach allows for maximising the utilisation of existing infrastructure, optimising resource allocation, and unlocking untapped potential within the energy system. Additionally, the local operation aspect presents a strength by enabling decentralised energy management, fostering community involvement, and promoting local resilience.

Several **weaknesses** are identified that need to be considered in the analysis. Potential aging of equipment is a significant concern raised; this highlights the need for careful monitoring, maintenance, and potential upgrades of the network to ensure the longevity and reliability of the infrastructure. Sub-optimisation of the EH, poses a weakness by potentially impacting the network beyond the energy hub, necessitating coordination and balancing of system-wide objectives. Moreover, the complex design associated with the utilisation of multiple grid components requires specialised knowledge and expertise for effective implementation and management. For example the level of organisation must increase if more than one substation is needed for the EH, or even if the connections to the exterior grid are in different cables as this would require higher levels of management.

The potential for more companies to connect and participate, presents an **opportunity** for increased collaboration, market integration, and diversification of energy sources. The adoption of innovative solutions opens doors for technological advancements, sustainable practices, and enhanced energy efficiency. Delaying grid reinforcement, offers an opportunity to explore alternative approaches, such as demand response and smart grid technologies, before resorting to costly infrastructure upgrades. Furthermore, the conversion of energy hubs can enrich and improve the energy system as a whole, through integrating various energy vectors, optimising resource usage, and promoting a more sustainable and resilient energy landscape. Moreover, energy hubs pose as an opportunity in the potential for well-organised groups to gain comprehensive energy system knowledge and consciousness, fostering collaboration, shared learning, and collective action.

Operating energy hubs closer to their operational limits poses a significant **threat** by increasing the risk of equipment degradation and system instabilities. This not only jeopardises the longevity and performance of the equipment but also leads to a reduction in flexibility and robustness. Additionally, the collapse of energy hubs presents another significant threat that can disrupt the reliability and stability of the entire energy system. Furthermore, the presence of energy hubs may inadvertently remove the sense of urgency for reinforcement investments in the grid, which can impede necessary upgrades and compromise the long-term reliability of the energy infrastructure. Addressing these threats requires careful monitoring, maintenance, contingency planning, and a sustained focus on grid reinforcement to ensure the resilience and stability of the energy system.

5.3.4. Goal 3: Increase the share of renewable energy

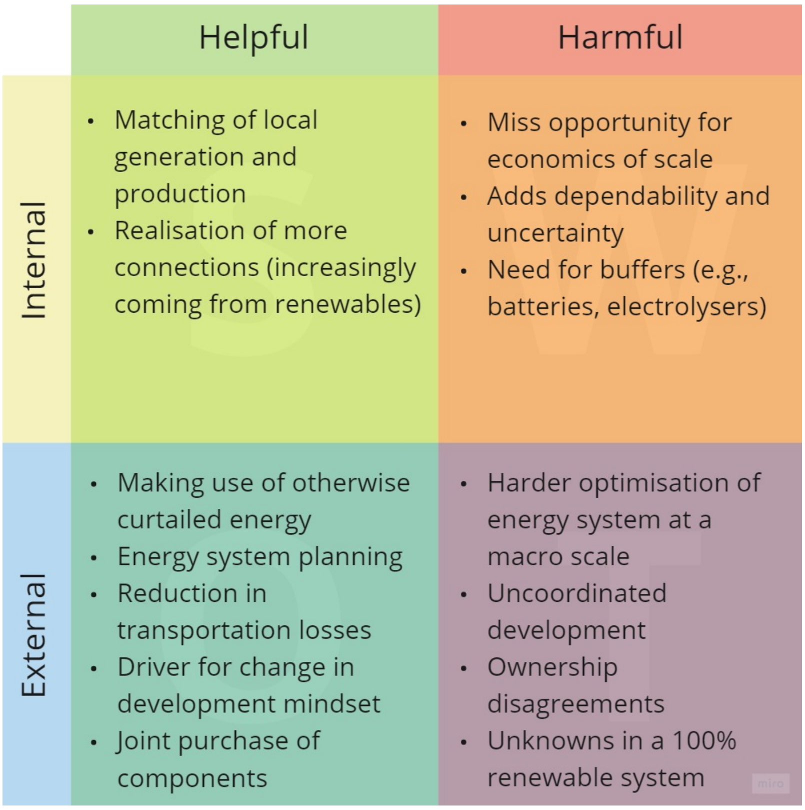

Figure 5.8: SWOT analysis for goal 3

Using energy hubs as a tool to increase the share of renewable energy in the Dutch grid offers several **strengths**. Firstly, energy hubs facilitate the matching of local generation and consumption, as highlighted by most interviewees. This localised approach enables efficient utilisation of renewable energy resources and reduces transmission losses. Additionally, energy hubs allow for more connections, particularly from renewable energy sources, supporting the integration of distributed generation into the grid.

However, there are also **weaknesses** associated with using energy hubs for this goal. A concern about energy missing out on economics of scale is raised as energy hubs may not be able to provide the same economics of scale that an approach that considers the full energy network can provide. Furthermore, the inclusion of renewable energy introduces complexities and uncertainties, which then need buffers, such as batteries, electrolysers, and boilers, which adds to the system's complexity and cost.

There are several **opportunities** associated with using energy hubs to increase the share of renewable energy. Firstly, energy hubs provide a means to utilise otherwise curtailed generation. This allows for the optimisation of renewable energy resources and reduces wastage. Energy hubs also offer opportunities for energy system planning, enabling coordinated integration of renewable energy sources into the grid. Additionally, energy hubs allow for coordination between the spatial vision of municipalities and the expansion vision of DSOs, fostering collaboration and synergistic outcomes. Furthermore, the use of energy hubs can result in reduced energy losses through transportation, contributing to overall system efficiency, as highlighted by Paul. Energy hubs also act as a driver for change in the development mindset, encouraging innovative approaches and solutions. Moreover, the concept of joint purchase of components within energy hubs can lead to shared economic benefits and cost savings, bringing further incentive for the use of certain components such as batteries or electrolysers that may have positive effects on the grid.

However, there are certain **threats** associated with using energy hubs for increasing the share of renewable energy. It is pointed out that it may be more challenging to achieve macro optimisation when relying on decentralised energy hubs, as these prioritise local usage resulting in a conflict of interest between the local and national system. The uncoordinated development of energy hubs can lead to inefficiencies and sub-optimal outcomes. Ownership disagreements among stakeholders can create obstacles and delays in the implementation of energy hubs. Additionally, there are still uncertainties and unknowns regarding the operation of a 100% renewable energy system, which may impact the feasibility and stability of energy hubs in the long run.

6 | Practical Analysis of the Value of Energy Hubs

This section chapter analyses the practical value of energy hubs by looking into two particular cases. The two cases analysed in this chapter are: a case study in Reimerswaal (section 6.1), followed by the ECUB project, in section 6.2.

Energy hub is a term loosely used in the practical world. Quite a few projects call themselves energy hubs, however do not satisfy all elements of the definition formulated through academic literature (in section 5.1.1). Regulation and legislation is behind involvements in technology and therefore the concept of EHs does not currently exist under Dutch law. Projects that classify themselves as energy hubs currently in development in the Netherlands are outlined in table 6.1, as per documentation given by Stedin. The two EHs highlighted in the table will be looked into further in this chapter. Both cases are analysed in order to gain a better understanding of what values can be gained practically by energy hubs.

Project name	Network Operator
CLIC	Liander
ArenA Energy Poort	Liander
SADC LES	Liander
Ijpolder ALEC	Liander
De Hoek - Tufsteen Amsterdam ALEC	Liander
De Zwette Leeuwarden ALEC	Liander
LAB Lelystad ALEC	Liander
Haven Den Helder	Alliander/Firan
Apeldoorn Noord	Alliander/Firan/Entrance
Energiehub Hessenpoort Zwolle	Enexis
Energiehub Almelo XL	Enexis
Energiehub Kempisch Bedrijven Park	Enexis
ECUB	Stedin
Reimerswaal	Stedin
Hoog Dalem	Stedin
Greenparc Bleiswijk.	Stedin
ECUB - CBP 2	Stedin
LEF in Eemnes	Stedin
Sterk op Stroom Den Haag	Stedin

Table 6.1: Current EHs in development in the Netherlands and their associated DSOs

The highlighted projects are happening under the Stedin network, neither is currently an energy hub (as defined in this paper using academic sources). However they both have the potential to become energy hubs, and initiatives happening in these areas are also interesting to look at to better understand what value energy hubs bring, and may bring to a changing energy system.

6.1. Reimerswaal

This section delves into the area of Reimerswaal. It firstly introduces developments, initiatives and challenges of the area in section 6.1.1. Once background is provided, an analysis is performed to determine if the project can be considered an energy hub in section 6.1.2. The actors in Reimerswaal are explored in section 6.1.3. Finally an analysis of the value added by the introduction of the energy hub concept in the area is performed in section 6.1.4.

6.1.1. Introduction

Reimerswaal is a municipality located in the south-west of the Netherlands, in the province of Zeeland. Reimerswaal is the site for various energy projects, many already in operation, others contracted, and others still being thought of. The electricity grid in Reimerswaal, like in many areas in the Netherlands, is gradually getting fuller and fuller. Stedin (who operates in this area) needs to be conscious of the growing capacity requests, as if these exceed a certain amount, then the area must enter ”congestion management” (see section 2.3.5). This can be a lengthy and complicated process. Expanding the grid in this area is also a complex undertaking due to the municipalities’ zoning planning (Gemeente Reimerswaal, 2022).

Therefore, forming an EH in this area could have significant advantages, and prevent the area entering into ”congestion management” or the expansion of substations. There are various stakeholders in Reimerswaal with varying generation and consumption types. Therefore a system that is able to optimally integrate different energy carriers could bring major financial, societal, and environmental advantages to the area.

The report ”De Groene Kamers van Rilland” (translates to: ”The Green Rooms of Rilland”) provides a future vision of how the area can evolve (Gemeente Reimerswaal, 2022). This paper envisions an increase in biodiversity, optimisation of fresh water, increase in sustainability of agriculture, improvement of recreational value, and generation of clean energy. Figure 6.1 together with table 6.2, give an overview of the projects happening in the area.

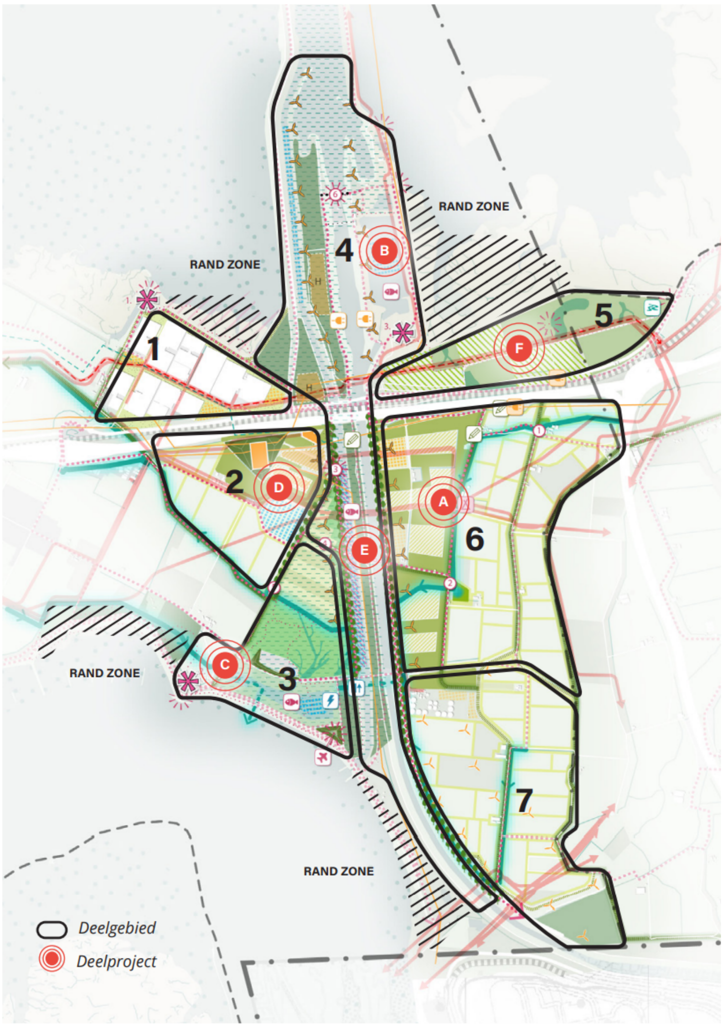

Figure 6.1: Schematic of Reimerswaal Project

A. Project East	Work is being done on multiple space use and smart energy management. Explicit links are made between sustainable energy and making agriculture, water and nature more sustainable. Wind and solar energy are being linked and smart solutions are being sought in which hydrogen and residual heat can be used locally as sustainable energy sources. Partners from the entire sub-area are working together on this project with the aim of linking tasks and spatially clustering energy and spreading it economically.
B. Project sun on water buffer basin RWS	Together with the government services and important partners in the area, the possibilities are being investigated to realise a floating solar park in which the link is made with recreation and nature value in the immediate vicinity. The links with wind energy are sought and preservation of the characteristic landscape value on the lock complex is a condition.

C. (Be)livable and energy-neutral Bath	Together with the inhabitants of Bath and important partners, quality of life, recreation in and around Bath is given substance. Nature, landscape and cultural-historical values are the underlying qualities. It is being investigated whether the realisation of a floating solar park on the Spuiboezem can contribute to this and make the households of the area energy neutral.
D. Revitalisation 1st Bathpolder	It is clear that the area south of the A58 could use a quality boost. Together with partners and the environment, it is being examined whether multiple use with energy projects and energy management can contribute to the quality of life in the area. Within this sub-area, the robust structure is important to better integrate existing infrastructure into the landscape. The water challenge will have a prominent opportunity to work together with the sustainability of agriculture and smart energy management.
E. Recreational and sustainable canal zone	Together with the Government Partners, we are investigating where and in what way work can be done on the robust green (main) structure in combination with recreation and sustainable energy. This area is also seen as an important connecting zone between other areas. Here too, powerful combinations can be made between improving nature and recreation with energy projects (on water).
F. New nature and recreation in the Hogerwaardpolder	Together with the partners involved, we are investigating how to contribute to improving nature, biodiversity, recreational values and safety in and around the polder. It is also being examined whether the polder can play an important role in hydrogen purchase for local (agricultural) use and mobility.

Table 6.2: Details on different locations from figure 6.1 adapted from Gemeente Reimerswaal, 2022.

6.1.2. Reimerswaal as an Energy Hub

To better understand to what extent the Reimerswaal area can be considered an EH, the limiting criteria identified in section 5.1.1 are analysed. The identified limiting criteria are:

- **Must have inputs that are conditioned into outputs:** This criteria is met in the envisioned projects, as in area A in figure 6.1 they are looking into hydrogen production and using residual heat locally (as described in table 6.2).
- **Must follow an optimisation strategy which leads to an increased efficient usage of the input variables:** It is made clear by the municipality their wishes to optimise the whole area (not just in terms of energy). An optimisation strategy would have to be implemented for the dispatchment of residual heat and the production of hydrogen.
- **Must have a finite spacial constraint:** This criteria is met in the vision.
- **There must be collaboration between the individual actors:** Currently there is no set collaboration between actors. There is no clear understanding of who the actors involved would be, however some actors have shown interest in being involved in this

project, e.g. , through considering changing their usual business model to also include other energy carriers. There are wishes for collaboration from different actors, however how this collaboration can happen is still not set, making this criteria an important one to focus on.

- **An EH operator must manage the system:** As there is still not a clear understanding of how collaboration between stakeholders will take place, there is also still no allocated EH operator. However, Stedin and the municipality of Reimerswaal have big interests in the projects, and when the time comes could either help operate it, or find a suitable operator.

From the criteria it is evident that Reimerswaal technically can become an energy hub, however it is missing the willingness for actors to collaborate. Therefore at this point in time it cannot be identified as an energy hub. The actors are further looked into in the following sections (6.1.3).

6.1.3. Actors in Reimerswaal

The collaboration between the different stakeholders is something of great importance, however not clearly established in the Reimerswaal area. There are some actors that have shown clear enthusiasm in partaking in an optimised system, however there are others that are not as eager, as they will not experience as many advantages. Consequently it is important to go into more detail about who is involved, what they have to gain, and what can be done to encourage the involvement. A power interest grid is provide in figure 6.2 to give insight on how the actors in the area are behaving.

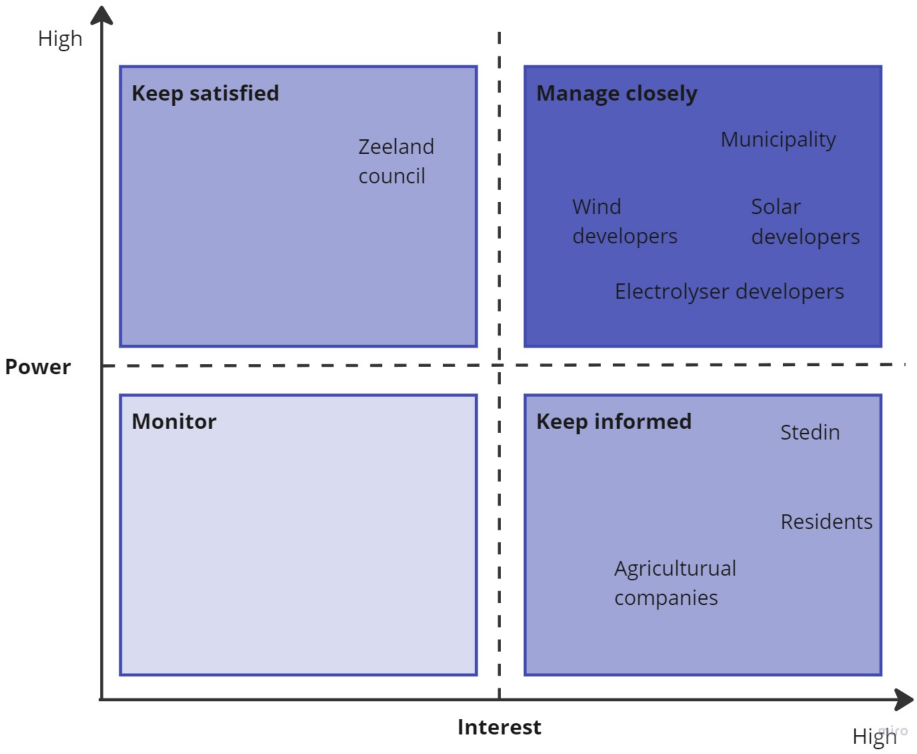

Figure 6.2: Power-interest grid for the stakeholders in Reimerswaal

Residents: They are placed as having high interest as they may be affected by the developments in the area. Their needs are being considered, as seen in the green rooms of Rilland - e.g. a diet including more greens, and recreational facilities

Agriculture companies: They have high interest, as the introduction of an EH can make their practices more sustainable, and potentially reduce costs. However they do not have as much power as it is not up to them if the project goes through or not.

Municipality of Reimerswaal: The municipality is very interested in optimising the area, evident in the report they came up with: ”The Green Rooms of Rilland” (Gemeente Reimerswaal, 2022). They are actively looking to make the are optimised in various perspectives. Transitioning to a cleaner and more sustainable energy system is definitely a priority, however there are also other ways in which components for the EH can be used to optimise other parts of the area; for example they are looking into using the byproduct of oxygen (from hydrogen production in the electrolyser) to be used in the water purification process in the area.

Energy providers (solar and wind developers): These may be any party involved in energy generation that wants to be involved in the EH. In the Reimerswaal area there are various generators, with already existing assets, contracted assets, and assets they still want to build.

Electrolyser developer: They have high interest in this formation of an EH as an optimised strategy will allow for profit maximisation. Moreover, they have high power, as their involvement is essential to add another energy carrier, therefore making the area an energy hub.

Stedin: Stedin is actively collaborating with the municipality and the different producing companies to help come up with a good design. They have high interest as the burden of providing the possibility of connecting to the energy system fall under them as a DSO. They do not have much power as, at this point, they do not get to make decision, or force participators to cooperate.

6.1.4. Analysis of Value Added

This section analyses the practical value of energy hubs by evaluating against set performance indicators. Firstly, the formation of these key performance indicators (KPIs) are described. Then, the KPIs are used to analyse two situations, firstly a business-as-usual situation, and secondly a situation where an energy hub is implemented.

Key Performance Indicators (KPIs)

It is important to establish criteria to evaluate the performance of the addition of an energy hub to the Reimerswaal area. To ensure coherency, and to maintain equivalence between the theoretical value analysis and practical application, the goals identified as significant for the DSO (in section 5.3.1) are employed in shaping the Key Performance Indicators (KPIs) under scrutiny in this section. Figure 6.3 shows a visualisation of how the KPIs are derived from the SWOT analysis goals.

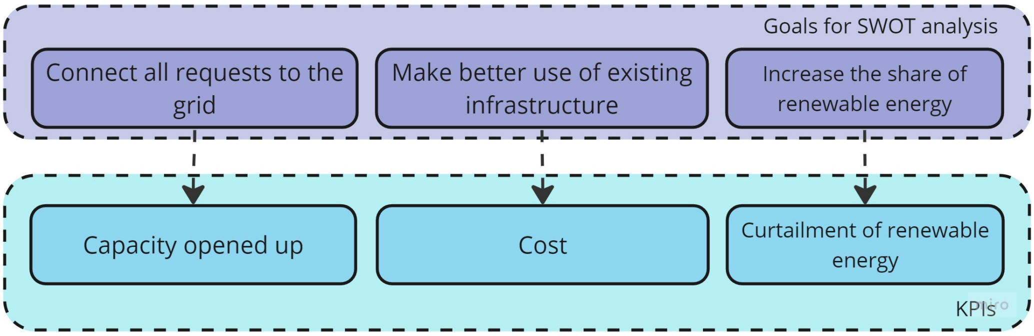

Figure 6.3: Formulation of KPIs to analyse the practical value of energy hubs

The translation of the goals into tangible and measurable KPIs is a pivotal step in the analytical framework. Each goal identified as crucial to Stedin's mission was meticulously transformed into specific KPIs that encapsulate the essence of the respective goal while enabling quantitative assessment. The process by which each goal is synthesised into its corresponding KPI is described below:

1. **Goal: Connect All Requests to the Grid -> KPI: Capacity Opened Up -** The primary focus of this goal revolves around equitable access to the energy grid for all connection requests. In line with this, the KPI evaluates the extent to which new grid connections have been facilitated. It quantifies the additional capacity made available for possible new connections, directly reflecting the achievement of the initial goal.
2. **Goal: Make Better Use of Existing Infrastructure -> KPI: Cost -** This goal underscores the importance of optimising grid infrastructure utilisation. The KPI assesses the financial implications associated with infrastructural enhancements. Reductions in maintenance, operational, and capital costs collectively denote the effectiveness of utilising existing infrastructure to its fullest potential, resonating with the essence of the goal.
3. **Goal: Increase the Share of Renewable Energy -> KPI: Curtailment of Renewable Energy -** This goal centers on the integration of renewable energy sources. The KPI measures the extent to which the integration of renewable energies is effectively managed. A lower level of curtailment indicates successful integration, as it results in minimised wastage of renewable energy due to operational constraints, aligning with the goal.

In essence, the transformation of these goals into quantifiable KPIs bridges the gap between theoretical aspirations and practical outcomes. This systematic approach ensures that each KPI reflects the essence of its corresponding goal and provides a reliable basis for evaluating the effectiveness of energy hubs in achieving Stedin's critical objectives. The subsequent analysis of these KPIs offers a comprehensive understanding of the contributions energy hubs make towards each goal, substantiating their real-world impact within the energy network landscape.

Business-as-Usual (BAU)

The Business-as-Usual (BAU) case represents the traditional approach that Stedin follows in a situation when connection requests exceed the capacity available at a particular location. From expert knowledge from the asset management department at Stedin the following conclusions on the reinforcements necessary for the site have been made (Stedin, personal communications):

- Stedin: approximately 16 million euros to be spent on reinforcements
- TenneT: would require a new 150 kV substation for 50 million euro
- Project lead time would be over 10 years
- Area would be locked for new initiatives

In the BAU case once the connection requests exceed the capacity available in the grid, the congestion management procedure shown in figure 6.4 is to be followed. Congestion management protocol is very recent and has only been added in May 2022 to the Dutch law, in article 9.10, the maximum budget that the DSO has for congestion management is: 1.02 euro/MWh per year of the amount of electricity that can be transported with the existing transport capacity in this congestion area during the period for which the congestion area has been designated. The law does not state how this should be allocated, just that this is the maximum budget allowed for the DSO to compensate different connections to curtail their electricity generation/-consumption.

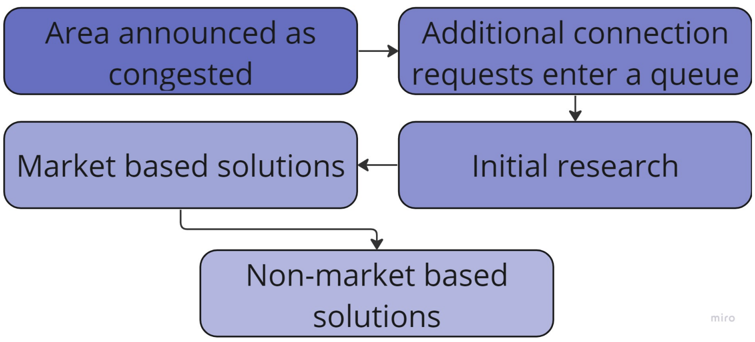

Figure 6.4: Congestion management procedure for business as usual (Stedin, personal communications)

This case assumes the following existing, new, and envisioned generation in the area (Stedin, private communications). The generation profiles of all the generating plants have been compiled and shown in figure 6.5 (orange line). The figure also shows the limit of the substation at 280 MW, clearly illustrating that a substantial portion of the power generated by these plants exceeds the designated technical capacity.

- Existing Solar - 33 MWp
- Existing Wind - 117 MWp
- Existing CHP - 20 MWp
- New Solar - 52 MWp
- New Wind - 80 MWp

- New Envisioned Solar - 40 MWp
- New Envisioned Wind - 40 MWp

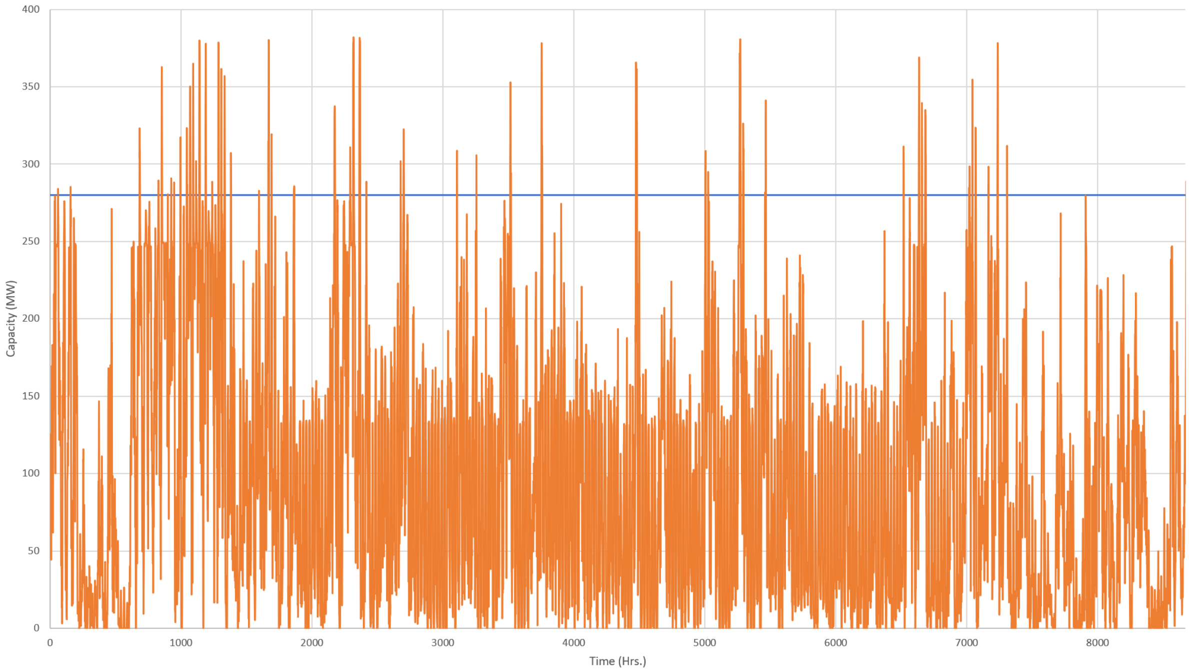

Figure 6.5: Accumulated capacity (orange) of all generation plants in Reimerswaal, compared to the substation capacity limit of 280 MW (blue)

The generation accumulated capacity exceeds the 280 MW substation limit only for 201 hours in a whole year (2.3%), moreover the total energy that exceeds the substation is equivalent to 8400 MWh. Considering the 1.02 euro/MWh, and assuming a 10 year project lead-time, Stedin would have the following budget to allocate towards congestion management whilst waiting for the reinforcements to be completed:

$$280MWh \cdot 1.02euro/MWh \cdot 10years \cdot 8,760 = 25,018,560euros \qquad (6.1)$$

Capacity opened up	Capacity will be opened up with grid reinforcements, however will take at least 10 years, locking the area for new initiatives.
Cost	Stedin has to bear a cost of 16 million euros in infrastructure, and an additional 25 million euros for congestion management. The costs do not consider further additional costs such as manpower and other operational costs.
Curtailment of RE	The project is expected to have a lead time of at least 10 years, until then 8400 MWh of renewable electricity will be lost every year. After that there will be further space for this excess capacity.

Table 6.3: Summary of the different KPIs for BAU case

Energy Hub Case

When formulating a future vision for the Energy Hub (EH) in Reimerswaal, several factors come into play. The design possibilities encompass diverse configurations with distinct inputs and outputs. This analysis takes into account the capacities of various generators as observed in the BAU case (depicted in figure 6.5). Additionally, the integration of an electrolyser is considered, introducing enhanced flexibility to the system through the inclusion of additional energy carriers. This, in turn, enables the region to fulfill the essential criteria that define energy hubs. Figure 6.6 gives a visual representation of the model that will be analysed, this is not a set model for the area, as changes may still be made. The diagram shows an external connection the the electricity grid where both solar and wind generation are connected. The electrolyser is connected to this grid and serves the purpose of supplying hydrogen to the Dutch gas backbone, which runs in close proximity to the area. Additionally, the electrolyser is intended to provide hydrogen for a hydrogen boiler, which will generate heat for the greenhouses in the vicinity. Furthermore, the residual heat from the electrolyser will also be utilised. The area is to be strategically optimised by taking into account industries beyond energy production. Unused products, such as the oxygen from the electrolyser, will be utilised for water purification purposes. This demonstrates the commitment of the involved actors to designing a system that maximises the efficiency of all aspects within the area. This emphasis highlights the area's potential to evolve into an energy hub.

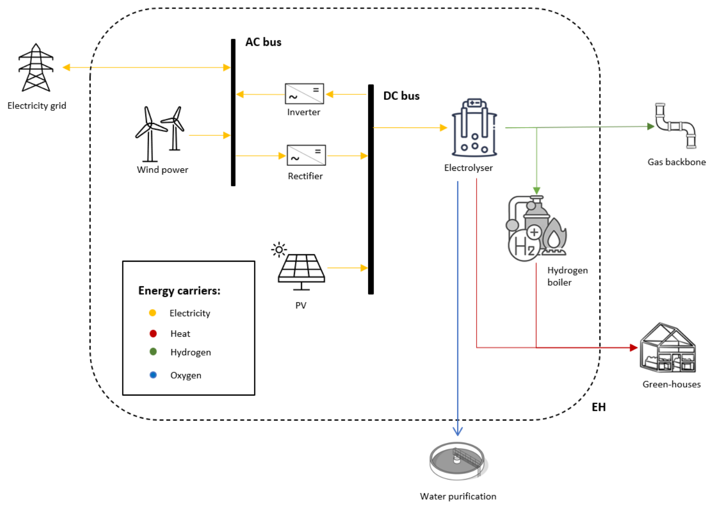

Figure 6.6: Diagram of the chosen energy hub model in Reimerswaal

To enable the analysis of the performance indicators for this case, the following **assumptions** are used:

- Size of the electrolyser is 60 MW, personal communications show that the size of the electrolyser will be around 60 MW.
- Electrolyser will operate for 5150 hours per year. This is the maximum allowed as per the SDE++ subsidy obtained for this project.
- Assumes the same generation as BAU.
- Assumes curtailment factors of 50% for solar and 70% for wind (Stedin, personal communications).

- Uses a PV and Wind factor that establishes a percentage of the capacity for each hour of the year (Stedin, personal communications).
- 280 MW substation, already considering a safety factor (Stedin, personal communications)

Using the above mentioned assumptions, a total of 6,912 MWhs of renewable energy in the Reimerswaal area can be saved annually. Table 6.4 shows the results for the amount of energy that the introduction of a 60 MW electrolyser can have in Reimerswaal.

Size of electrolyser	Total MWh unused without electrolyser	Total MWh saved by the electrolyser	Total MWh unused with electrolyser	Percentage saved
60	8400	6912	1488	82,3%

Table 6.4: Results of the effect of an electrolyser on the curtailed electricity in Reimerswaal

It is clear that a 60 MW electrolyser wont be able to make 100% use of the otherwise curtailed electricity, a further study into how the size of the electrolyser effects the percentage saved is conducted. Further electricity can be saved if the size of the electrolyser is increased, figure 6.7 shows the relationship with the percentage of energy saved and the size of the electrolyser. It is evident that by increasing the size of the electrolyser more of the electricity that would have been otherwise curtailed (since generation exceeds the substation capacity limit) can then be used to generate hydrogen, therefore removing this pressure from the grid.

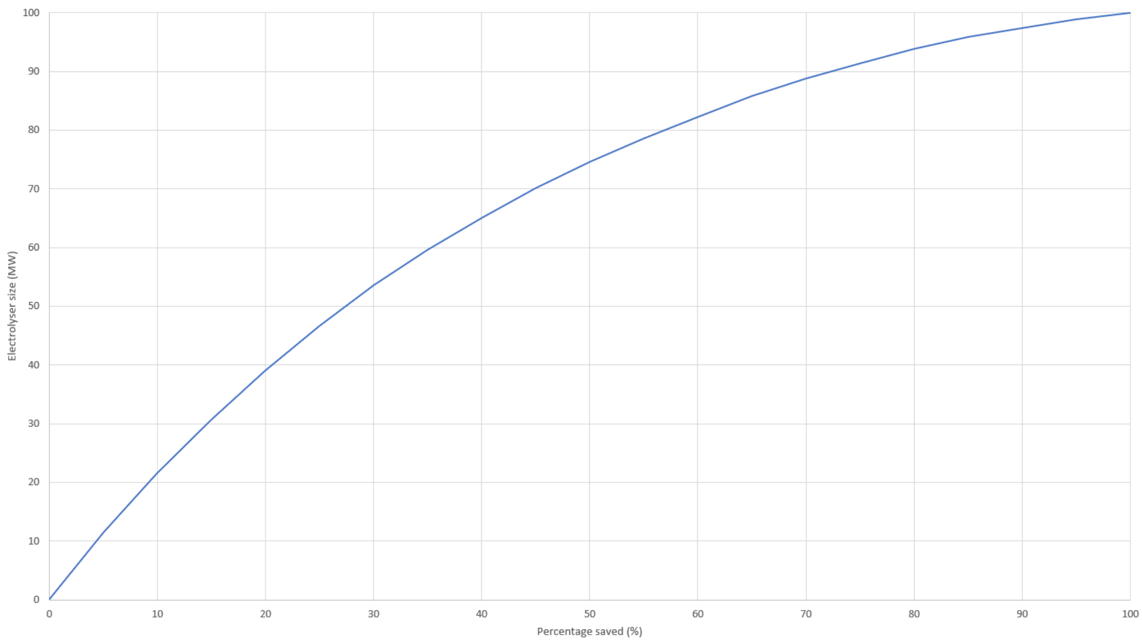

Figure 6.7: Graph showing the relationship between the percentage of electricity that is saved (x-axis) with changing electrolyser size (y-axis)

If all generations are running at their maximum potential, a total of 382 MWs are generated, exceeding the grid capacity by 102 MWs. This only happens for 201 hours per year, however if all energy produced in Reimerswaal is wished to be utilised, then an electrolyser of 102

MWs is needed. As the size of the electrolyser gets closer to 102 MWs limit, it is clear that the increase in percentage of energy saved slows down.

It is important to outweigh the cost of increasing the electrolyser with the amount of electricity it is able to save. The IEA (international Energy Agency) states that the cost of a PEM electrolyser ranges from USD 1,100-1,800/kWe (IEA, 2023). Taking the largest value for this range this amounts to close to 1.6 million euro/MWe. Figure 6.8 show how much it would cost to open up further capacity by increasing the size of the electrolyser. In order to fully open capacity (have 0 unused MWs of electricity) a further 64 Million would be needed to increase the electrolyser by 40 MW.

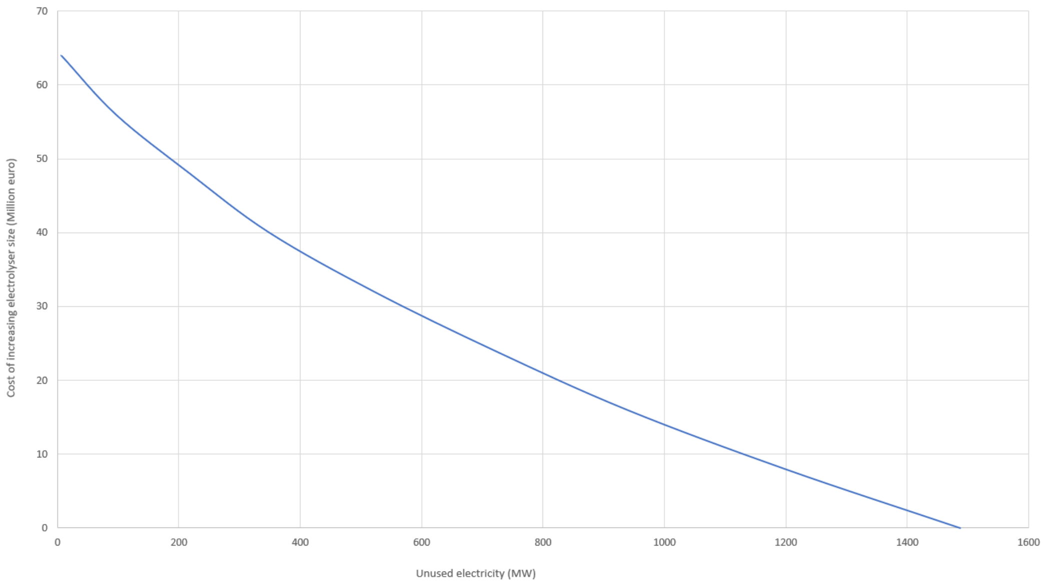

Figure 6.8: Graph showing the relationship between the cost of increasing electrolyser size (y-axis) versus amount of excess electricity (x-axis)

Even though the 60 MW electrolyser cannot fully make use of this excess electricity, it does a good job at lowering the amount of hours of excess in electricity and in lowering the MWs that exceed the substation's capacity. With this reduction a much lower budget is needed for congestion management in the area, making congestion management much more feasible in comparison. Figure 6.9 shows how many hours the generation capacity exceeds the substation capacity with and without the electrolyser. From the graph it is evident that the addition of an electrolyser substantially decreases the amount of time the substation capacity is exceeded.

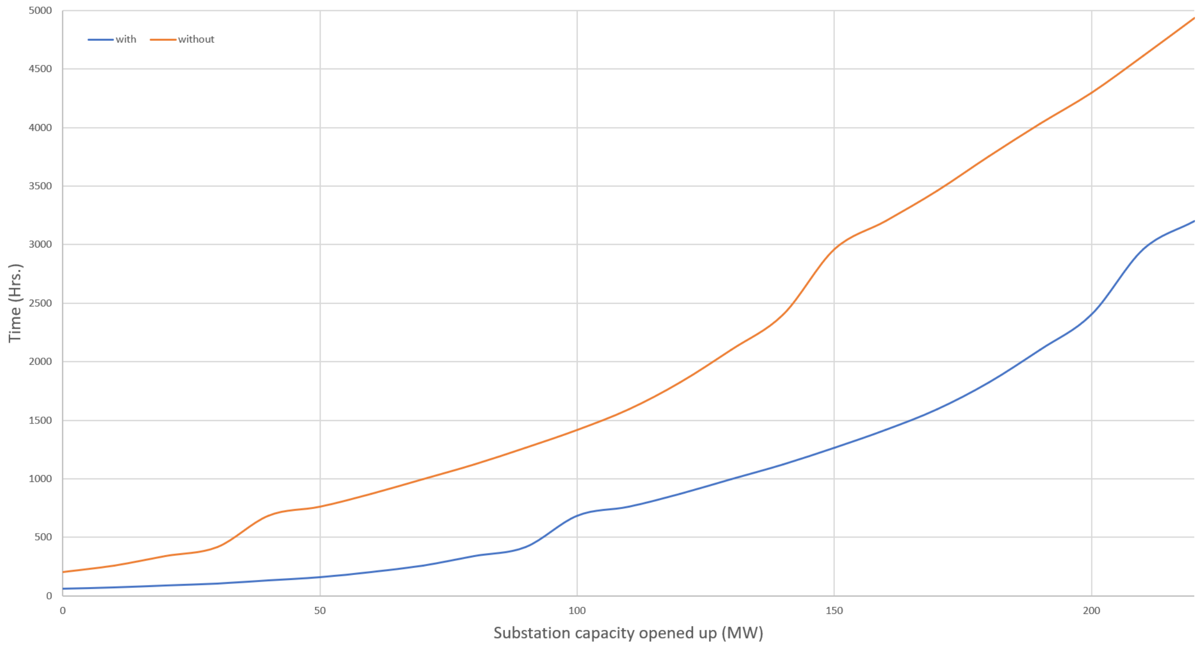

Figure 6.9: Graph showing the amount of hours when capacity exceeds substation capacity (y-axis) in relation to how much capacity is opened (x-axis) up with (blue) and without (orange) a 60 MW electrolyser

Capacity opened up	Capacity cannot be directly opened up, however the amount and the frequency of generation capacity that exceeds the substation limit is substantially lowered, lowering the needed congestion management budget.
Cost	None by the DSO, costs fall under the developper currently looking into the electrolyser. Increasing the size of the electrolyser can help the DSO manage congestion in the area and therefore is a venture of potential interest to the DSO.
Curtailment of RE	A total of 6,912 MWhs of renewable energy saved, making up above 82% of otherwisecurtailled energy. This can be increase to 100% by increasing the size of the electrolyser, however this would cost around 64 million euros.

Table 6.5: Summary of the different KPIs for EH case

6.2. ECUB

This section takes a deeper look at the ECUB project. The introduction in section 6.2.1 provides background on the project. This is followed by a section (6.2.2) analysing weather the project aligns with the definition of an energy hub. Section 6.2.3 examines the actors involved, and section 6.2.4 assesses the value added by this project.

6.2.1. Introduction to ECUB Case

The ECUB case is located in Lageweide in Utrecht. ECUB stands for: Energie Collectief Utrechtse Bedrijven (in English: Energy Collective Utrecht Companies), this collective has the ambition to enable further growth in the energy network. ECUB is a pilot project that is testing out the EH concept and contracts that go along with it.

The municipality of Utrecht has high climate ambitions and has already put some plans in place to achieve them, including fossil-free logistics (Stedin, personal communication). This is leading to a faster growth of capital demand resulting in a higher strain on the grid, with capacity reaching its limits in the local 10kV grid. Even though this is not the case for the region, ECUB initiated this project to get ahead of the problem where different companies in Lageweide join to share cable capacity, lowering the demand on the local grid. This will consequently result in more capacity space in the substation, allowing for future entries to the grid in the area or for existing connections to increase their capacity. This will bring new opportunities for the existing companies, but will also stimulate economic developments through a strengthened business climate.

The companies involved will share their contracted capacity to reduce theirs costs. They will keep their individual ATOs, however will form a new contract, called a ”balancing contract”. This contract is between the grid operator and the collective group of the involved individuals. Figure 6.10 shows a simplified model of the system. It shows a substation with various connection points. The orange dots represent companies connected to the substation that will form the collective (indicated by the dotted orange line), and the white dots represent companies that are connected to the station that will not participate. The companies that will participate are the larger consumers, therefore their participation has a much higher impact than the others (Stedin, personal communications).

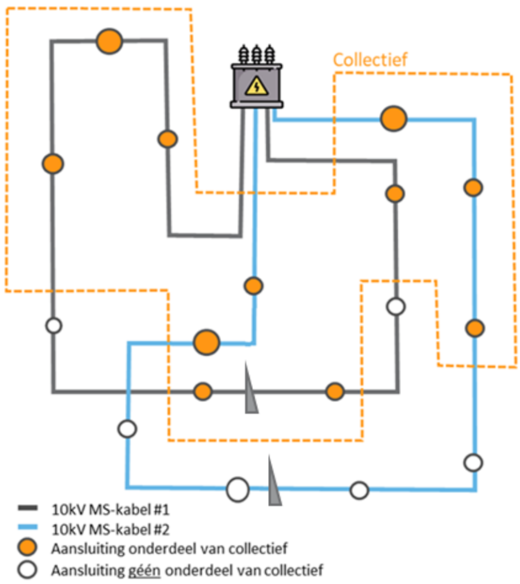

Figure 6.10: Schematic of ECUB Project (Stedin, personal communications)

6.2.2. ECUB as an Energy Hub

The ECUB project is currently referred to as an energy hub, however it does not comply with all the characteristics outlined in academia. The identified limiting criteria are:

- **Must have inputs that are conditioned into outputs:** This does not happen. The only energy carrier present in this case is electricity, it is never converted into any other type of energy carrier and there are no plans currently to include other energy carriers.
- **Must follow an optimisation strategy which leads to an increased efficient usage of the input variables:** This is the case with ECUB to an extent. The input electricity from the grid is wished to be more efficiently used through a more optimised use of the cable capacity.
- **Must have a finite spacial constraint:** Yes, this is evident in figure 6.10 from the dotted orange line, representing where the EH's boundaries are.
- **There must be collaboration between the individual actors:** This is definitely the case of ECUB. The different actors involved have created a legal group.
- **An EH operator must manage the system:** Within the group formed there is someone in charge managing the group.

The term energy hub in this context can be classified as a misnomer. It is being used incorrectly to name this type of project since it the project does not consider other energy carriers other than electricity. This is a limiting criteria, therefore the ECUB project cannot be technically classified as an energy hub. Reimerswaal also does not meet all the criteria, however, it is on the way to do so with ongoing conversation to introduce further collaboration between the stakeholders. On the other hand, ECUB doe not have any plans to include other energy carrier in its system.

For this case, it is interesting to compare the project to other concepts (see section 2.3), as it very closely resembles them.

From the description of the project being that the different companies involved will share the capacity of the cable, the first concept that ECUB can be compared to is **cable pooling**. Cable pooling in done with different types of of generation, whereas ECUB involves demand connections. So it cannot be cable pooling as recognised by the law, however it may be considered a type of *cable pooling for demand*. It is technically the same concept, however instead of sharing cable capacity to supply to the grid, it is sharing cable capacity to demand from the grid.

Another comparable concept is the **virtual power plant (VPP)**. Once again the works with generation (as indicated by the name), and ECUB works with demand. Therefore a different term can also be used here, for example a *virtual demand center*. Another difference is that VPPs do not have to be physically constrained, there may be different generation sites far away that are connected virtually. With ECUB, all the demands are connected to the same substations and will be managed virtually.

6.2.3. Actors in ECUB

The collaboration between the actors in the ECUB case is much more organised and evolved compared to the Reimerswaal case. The initiative that led to this project came from the local energy cooperation; the companies involved saw the Schiphol Energy Hub. They were inspired to take the initiative to build a similar concept for the area. The levels of congestion in the area are not high, and there are currently no restrictions in connecting to the energy system in the area, however the energy cooperation wanted to make a pilot project in order to get ahead of the problem. This shows a high level of willingness to collaborate from the different parties involved. As shown in the previous section, collaboration between the different actors is something that ECUB definitely has. Since the collaboration between the actors is more established, the power-interest grid for the actors in ECUB contains less actors (as shown in figure 6.11).

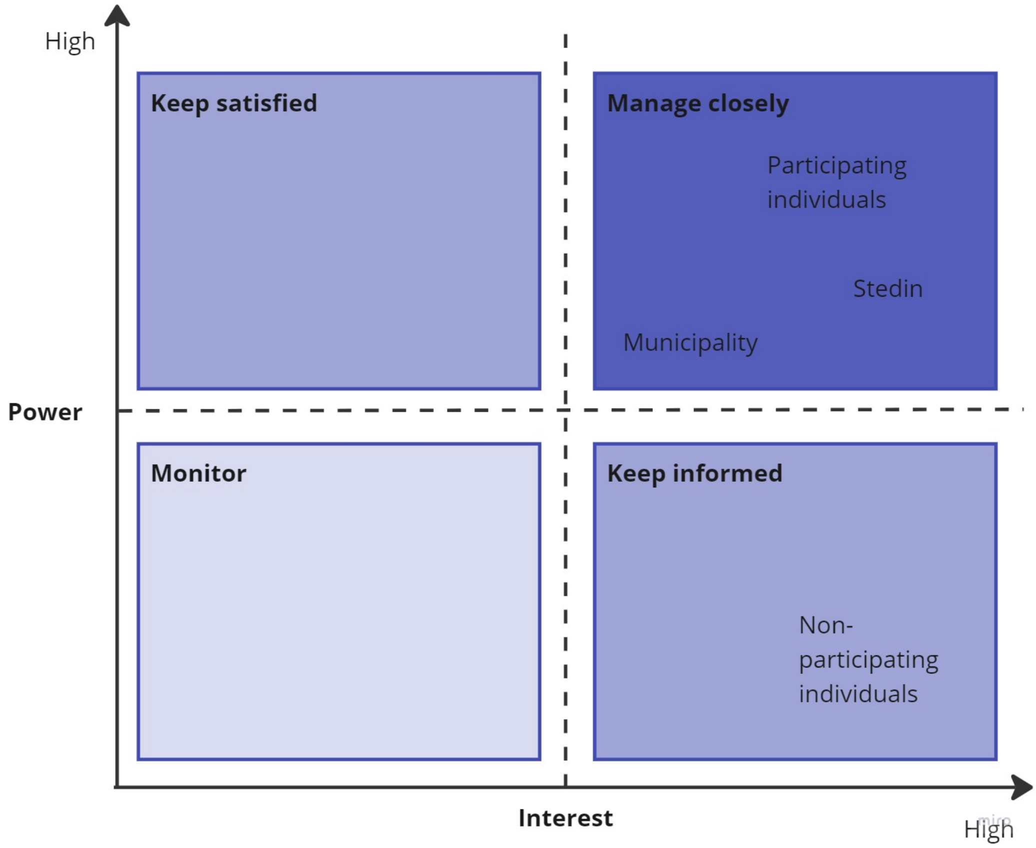

Figure 6.11: Power interest grid for the actors in the ECUB energy hub

Figure 6.11 places the actors involved in a power-interest grid. It uses the definitions of "power" and "interest" as formulated in section 5.2 to determine the placements. The following paragraphs give the reasoning for each position:

Participating individuals: The participating individual are the companies that make up the "collectief" as shown in figure 6.10. These are the companies represented by the orange dots. They have high power and interest as they were the ones taking the initiative and forming the project. The companies forming this collectief have their individual ATOs and are the companies with higher contracted capacities.

Municipality of Utrecht: The municipality has high interest and power. This project is predicted to result in a stimulation of economic developments in the area and strengthening of the business climate through collaboration between the different companies. It also has high power as the local facilitator, moreover Utrecht has ambitious CO_2 emission reduction goals pushing the municipality to come up with innovative solutions to solve this problem.

Stedin: Stedin has the role of facilitating the establishment of the EH by providing insight into the network structure. It does this because it has high interest in this project. Even though the area is not congested at this point (meaning it is not an area of high importance in congestion management for Stedin), this pilot project can give important insights in the development process of energy hubs. For example, this project is testing out "balancing contracts" which can be a good tool in the future for other projects. Therefore, even though this particular case might not be of upmost importance in the standpoint of resolving congestion, it can help build tools for other projects, making it of high interest for Stedin. Contrary to the power-interest grid for a generalised energy hub (5.2) and for the Reimerswaal case (6.1.3), Stedin is placed with high power.

Non-participating individuals: These are the companies that are not part of the collectief in figure 6.10, represented by the white dots. They have a much smaller load capacity and their involvement would have limited effects. Nonetheless they have high interest, they are physically connected to the companies participating in the energy hub as they are all connected to the same substation through the same cables. This means that actions taken by the group could directly affect them. Moreover, in the long-term the collectief may grow and these companies may want to join (depending in the success of the collectief).

6.2.4. Analysis of Value Added

It has been established that ECUB is not actually an energy hub as it does not have essential components to satisfy the definition made from academic literature. It lacks the multi energy carriers component, making it more of an “electricity hub”. Moreover, since the area does not currently experience congestion, and the initiative to look into this project came from individual interest of the actors involved, as opposed to a necessity for introducing an innovative solution to deal with bottlenecks introduced by a congested grid. ECUB does not experience congestion challenges, as there is still significant capacity space in the local grid, moreover it is not an actual energy hub (as defined in this paper). Without this key characteristic, increase in flexibility and other advantages gained through the EH configuration no longer apply. Because of this, the analysis applied to Reimerswaal does not make sense to be also be applied here.

However, the project does bring in other advantages, primarily in the increasing knowledge for all stakeholders and posing as a pilot to test out different techniques, including contracts, and getting stakeholders to collaborate. Some points from the previous section (5.3), can be also be applied to this project (and in many cases the interviewees drew knowledge from experience gained from this particular project). Information gained through interviews, and from documents sent (presentations) by the company, identify the following values:

- **Customer Engagement and Behavioral Insights:** The initiative promotes active engagement with customers, offering valuable insights into their energy consumption patterns and behaviors.
- **Hands-on Experience:** ECUB provides a conducive environment for stakeholders to gain practical experience with contracts and tools essential for energy hubs, fostering a deeper understanding of their functionalities.
- **Enhanced Energy Consciousness:** Through ECUB, stakeholders have an opportunity to enhance their awareness of energy-related issues and contribute to their resolution through informed decision-making.

while ECUB may not fit the academic energy hub mold, it showcases alternative advantages and learning opportunities to tackle important challenges within energy hubs. By shedding light on these benefits, this analysis highlights the importance of recognising the diverse contributions that initiatives like ECUB can offer, enriching the broader discourse on energy innovation and sustainability.

7 | Discussion

This chapter uses all the gathered information and analysis to answer the research questions. Each sub-research question is answered in sections 7.1, 7.2, 7.3, and 7.4. These sub research questions are then used to answer the main research question in section 7.5. It is also essential to reflect on the limitations of the methods used to analyse the different questions, this is done so in section 7.6.

7.1. What are the key components and objectives of an energy hub?

The section answers the first sub-research question. This question is answered using section 5.1, with the made methodology being literature review.

An energy hub comprises several key components and objectives. Understanding these components and objectives is crucial to the DSO because they may have significant effects on the rest of the network.

The components of an energy hub can vary depending on the classification, but they generally include inputs, converters, storage devices, and outputs. Inputs can consist of various energy carriers, with the electricity grid and natural gas network being the most commonly used. Converters play a crucial role in transforming energy carriers, and examples include combined heat and power systems, heat pumps, and fuel cells. Storage devices, while not essential, provide flexibility and can include electrical storage, thermal storage, and hydrogen storage. Outputs of an energy hub depend on the demand and can encompass electricity, heating, cooling, hydrogen, and more.

The objectives of an energy hub are focused on optimising the use of system components. This optimisation can be used to achieve various goals, such as decreasing energy prices, maximising renewable energy integration, and utilising space and resources efficiently. To achieve optimisation, different smaller objectives can be investigated to optimise the conversion, transmission, and storage of different energy carriers. These objectives include optimising energy exchange between equipment to reduce transmission losses, optimising energy exchange with transmission and distribution systems, optimal charge and discharge for battery systems, optimal bids in day-ahead markets, and optimal scheduling of output dispatch.

Furthermore, new studies are considering carbon emissions and the carbon market in energy hub modelling. Calculating carbon emission flows within an energy hub enables the optimisation of emission levels. By including a reduction in carbon emissions as an objective in the optimisation function, energy hubs can competitively bid in the carbon market as well.

Understanding and incorporating these components, objectives, and considerations is vital for the DSO. It allows for informed decision-making, efficient network management, and the ability to maximise the benefits of energy hubs within the overall energy system.

7.2. Who are the actors involved, what are their roles, and how can they benefit?

This section answers the second sub-research question. Energy hubs involve multiple stakeholders who play crucial roles in the energy system. Section 4.3.1 conducts an actor analysis; from this analysis, the actors involved can be grouped into various categories, and understanding their roles, interests, and potential benefits is essential for navigating the complexities of energy hub implementation.

Participating individuals are at the core of the energy hub. Within this group, there are two categories. ”New entry” individuals are those who have not yet secured a grid connection but are eager to collaborate with others in the area. Their participation in the energy hub can expedite their projects and provide access to shared resources and improved efficiency. ”Existing connection” individuals already have a grid connection and may have diverse interests in participating. While they have a secure means of dispatching or receiving electricity, they may still see advantages in joining the energy hub. They may wish to diversify their energy carriers or increase their connection capacity, granting them negotiation power due to their existing grid access.

Municipalities play a significant role as primary facilitators of local energy transitions. They have the autonomy to adopt environmental policies and make decisions tailored to their specific areas. The roles and interests of municipalities vary depending on their goals and priorities. They possess valuable knowledge about local needs and serve as vital contributors to the promotion and realisation of energy transition at the local level.

The Authority for Consumers and Markets (ACM) acts as the Dutch energy regulator and ensures fair competition and independent supervision of the energy market. Its role is to maintain stability and enforce compliance with regulations, contributing to the proper functioning of energy hubs.

Distribution System Operators (DSOs) have a high level of interest in energy hubs as they are responsible for connecting all actors within the grid. Their role is pivotal in facilitating the integration of energy hubs into the existing distribution system. They bear the responsibility of ensuring efficient and reliable energy distribution within the hub.

Non-participating individuals, who reside within the same geographical area as the energy hub but are not directly involved, can be consumers, producers, or prosumers. Consumers may be interested in potential changes in energy prices resulting from the energy hub. Producers might be concerned about the evolving energy landscape, as it could impact their future plans.

Environmental organisations prioritise environmentally-friendly practices and advocate for the protection of the environment. In the context of energy hubs, they strongly support the integration of renewable energy sources and green technologies, aligning with their mission and goals.

The Ministry of Economic Affairs and Climate Change holds the responsibility of creating a conducive business climate and promoting growth and innovation through sustainable development of the energy system. They implement policies that encourage the establishment and success of energy hubs, aligning with the broader national goals of sustainable energy.

Gasunie, as the operator and manager of large-scale gas infrastructure in the Netherlands, typically has lower interest and power in energy hubs. Energy hubs primarily operate at the distribution level, falling within the domain of distribution operators rather than large-scale gas infrastructure management.

TenneT, as the transmission system operator (TSO) of the Dutch electricity grid, generally has limited interest and involvement in energy hubs, which typically operate at the distribution level. However, there may be specific cases where TenneT's interest and influence become more significant based on the project's scope and nature.

Each actor within the energy hub ecosystem brings unique perspectives, interests, and responsibilities. Effective management and engagement of these actors can leverage their expertise, foster cooperation, and garner support, ultimately leading to successful implementation and operation of energy hub projects.

7.3. What makes energy hub a successful tool in achieving policy goals important to the DSO?

This section answers the third sub-research question. Energy hubs can serve as a successful tool in achieving policy goals important to DSOs for several reasons. Three key goals relevant to DSOs have been identified: connecting all requests to the grid, making better use of existing infrastructure, and increasing the share of renewable energy. Assessing these goals through a SWOT (Strengths, Weaknesses, Opportunities, Threats) analysis provides insights into the benefits and considerations of EHs in achieving these objectives. This analysis is conducted in section 5.3.

Goal 1 focuses on connecting all requests to the grid. EHs offer strengths in this area, as they enable more efficient utilisation of capacity, potentially unlocking additional capacity for connection requests. The collaborative nature of EHs fosters coordination among stakeholders, promoting collective problem-solving and synergistic outcomes. However, EHs also face weaknesses, such as the need for specialised knowledge and competence for efficient management and operation. Limited control over components within EHs can impact overall grid stability. Additionally, concerns exist about the capacity of EHs to handle increasing demands effectively. Opportunities lie in customer engagement and gaining insights into their energy needs, as well as the potential for joint investments and shared economic benefits. Threats include participants not changing their behaviour, inequitable access and treatment, equipment ageing, and challenges in ensuring contractual obligations are upheld.

Goal 2 focuses on making better use of existing infrastructure. EHs offer strengths in maximising capacity utilisation and optimising resource allocation. The local operation aspect enables decentralised energy management, community involvement, and local resilience. Weaknesses include potential equipment ageing, sub-optimisation of EHs, and the need for specialised knowledge for implementation and management. Opportunities arise in increased collaboration, market integration, and diversification of energy sources. Delaying grid reinforcement through EHs allows for exploring alternative approaches before costly infrastructure upgrades. Threats include equipment degradation, system instabilities, potential removal of reinforcement urgency, and complexities in operating EHs close to their limits.

Goal 3 aims to increase the share of renewable energy. EHs provide strengths in matching local generation and consumption, optimising renewable energy utilisation, and supporting distributed generation integration. Weaknesses include potential missed economics of scale and increased complexity and cost associated with buffering renewable energy fluctuations. Opportunities lie in utilising otherwise curtailed generation, coordinated integration of renewable sources, collaboration between municipalities and DSOs, and reduced energy losses. Threats include challenges in achieving macro optimisation, uncoordinated development of EHs, ownership disagreements, and uncertainties in operating a fully renewable energy system.

By leveraging the strengths, addressing the weaknesses, capitalising on the opportunities, and mitigating the threats associated with EHs, DSOs can effectively utilise EHs as a successful tool in achieving their policy goals. EHs provide opportunities for grid optimisation, cost savings, customer engagement, collaboration, and innovation, while also requiring careful management, infrastructure maintenance, and coordination to ensure the resilience and stability of the energy system.

7.4. In practice, what opportunities and threats do energy hubs present to the DSO?

This section answers the fourth sub-research question by looking at the practical value of energy hubs by considering two case studies of projects that are classified as energy hubs, these are analysed in chapter 6.

The analysis of the two case studies was approached differently due to their inherent differences. In the case of ECUB, it was determined that it does not meet the conditions of an energy hub as it does not incorporate multiple energy carriers. However, in the Reimerswaal case, the introduction of an electrolyser enables the possibility of transforming it into an energy hub. Furthermore, the criteria used to assess the Reimerswaal case cannot be directly applied to ECUB since the latter does not face congestion issues or the need for infrastructure expansion, resulting in no additional costs or capacity requirements in the area.

Considering the aforementioned, a case like ECUB still poses some opportunities to the DSO common to other pilot projects. Overall, a pilot project offers the DSO an opportunity to gain practical experience, engage stakeholders, drive innovation, and contribute to the successful implementation of energy hubs. ECUB provides a platform for learning, experimentation, and gaining valuable insights into the implementation and management of energy hubs. Through such a project, the DSO can identify best practices, learn from challenges, and refine future energy hub deployments. This includes important considerations such as contracting, where the pilot project offers an opportunity to develop robust agreements that address various scenarios, including the inclusion of an exit clause and outlining responsibilities if the energy hub group decides to discontinue the project. Moreover, projects such as ECUB foster stakeholder engagement and collaboration by bringing together energy producers, consumers, communities, and technology providers. This collaboration promotes knowledge sharing, builds relationships, and creates a sense of ownership among stakeholders. Partaking in such a project can also be an opportunity for the DSO to enhance its reputation as a forward-thinking organisation by showing their commitment to innovation and sustainability.

On the other hand, ECUB poses a threat to Stedin's resource allocation strategy. Given that the ECUB area does not face congestion issues, the resources allocated to this project could potentially be better utilised in areas that would further benefit. Another threat associated with ECUB is the possibility that participants in the ECUB collective do not modify their consumption load patterns, resulting in minimal practical value added to the grid. When establishing a group contract like ECUB, there is a risk of no significant changes occurring, leading to a reduced income from tariffs as the total group capacity decreases. Therefore, Stedin must exercise caution to ensure that companies/entities do not form an energy hub as a means to obtain additional capacity without paying extra tariffs or to pay less for the same consumption behavior. These threats highlight the importance of forming an energy hub only if there are alterations in consumption patterns that can lead to more optimised utilisation of transport capacity, thereby benefiting both Stedin and the participating companies.

The analysis of the Reimerswaal case provides valuable insights into the opportunities and threats associated with implementing an energy hub that aligns with the academic definition, emphasising the inclusion of multiple energy carriers. This case compares the conventional approach of expanding the grid, which would be highly costly due to spatial constraints, with an alternative option of incorporating an electrolyser in the area. The addition of an electrolyser presents an opportunity to alleviate the strain on the substation, considering the existing, contracted, and future projects that collectively exceed the substation's capacity limit. Implementing an energy hub through the integration of an electrolyser would significantly reduce costs for the DSO while enabling the utilisation of renewable energy that would otherwise be curtailed. Furthermore, the electrolyser has the potential to create capacity openings in the substation, facilitating future connections and system flexibility.

However, it should be noted that the opening up of capacity is not fully achievable solely through the use of an electrolyser, as its size cannot cover the entire excess capacity. Although increasing the size of the electrolyser to match the exceedance could solve this issue, it remains a costly endeavour. The exploration of an electrolyser in the area is being undertaken by a private developer, with the associated costs borne by them. An analysis has been conducted to determine the cost of increasing the electrolyser size to eliminate capacity exceedance, revealing that it would be prohibitively expensive for Stedin, amounting to approximately 64 million pounds compared to the projected 16 million pounds in the conventional business-as-usual scenario. This case demonstrates that while the addition of an electrolyser is beneficial, it may not be sufficient to address congestion concerns. Additional measures are required, such as compensating individuals through congestion management or introducing further demand in the area. Another threat identified in this case is the potential unwillingness of actors to cooperate. The analysis assumes collaboration among all generation owners connected to the substation, which may not currently be the case, highlighting the somewhat theoretical nature of the analysis.

In conclusion, the analysis of various cases reveals that energy hubs present both opportunities and threats to the DSO. Pilot projects provide valuable learning experiences, stakeholder engagement, and innovation potential. They allow for the development of robust agreements and demonstrate the DSO's commitment to sustainability. However, challenges arise in terms of resource allocation, potential lack of value addition, and the need for substantial changes in consumption patterns. Additionally, the analysis highlights the benefits of integrating multiple energy carriers, such as reducing costs and enabling the utilisation of renewable energy. However, it also emphasises the complexity of addressing congestion issues and the importance of collaboration among stakeholders. Overall, energy hubs require careful consideration, adaptation to specific contexts, and proactive measures to maximise opportunities and mitigate threats for the DSO.

7.5. Main Research Question

How can energy hubs contribute to network management in the Dutch energy system?

Energy hubs offer significant contributions to network management within the Dutch energy system, with their ability to integrate various energy carriers and actors into one system. One key aspect is their role in addressing congestion and facilitating access to the energy system. By connecting more requests to the grid, energy hubs optimise resource allocation, reduce waiting lists, and enhance overall grid efficiency.

Another vital contribution of energy hubs lies in their potential to maximise the utilisation of existing infrastructure. By making better use of the grid, energy hubs minimise the need for costly expansions and reduce the financial burden on DSOs and end-users. This cost-saving aspect is particularly important, as grid expansion projects can be financially demanding and time-consuming. Energy hubs enable a more efficient allocation of resources, which ultimately leads to lower costs for grid operation and maintenance.

Furthermore, energy hubs play a crucial role in promoting the integration of renewable energy sources. As the transition to a sustainable energy system gains traction, energy hubs facilitate the integration and management of renewable generation. They enable the matching of local renewable energy production with local consumption, reducing transmission losses and optimising the utilisation of renewable resources. This contribution is essential for achieving the broader goal of increasing the share of renewable energy in the Dutch energy system.

In addition to their technical benefits, energy hubs foster collaboration and coordination among key actors. By bringing together energy producers, consumers, communities, and technology providers, energy hubs create an environment for knowledge sharing, innovation, and collective decision-making. This collaborative approach enhances the resilience and customer-centricity of the energy system by considering diverse perspectives and leveraging the expertise of various actors.

However, the implementation of energy hubs also poses challenges and limitations for network management. The reliance on multiple energy carriers and the management of diverse actors require careful planning, coordination, and regulatory frameworks. Issues such as resource allocation, stakeholder cooperation and contractual obligations may arise and need to be effectively addressed. Stakeholder engagement and effective communication strategies are crucial for successfully implementing and managing energy hubs.

To maximise the value of energy hubs, several actions should be considered. Firstly, achieving a nationwide consensus on the definition of energy hubs is essential to ensure a consistent understanding and avoid misinterpretation. Secondly, implementing a standardised legal procedure with established contracts would provide clarity and alleviate hesitations among potential collaborators. By formalising the definition of an energy hub the present ambiguity is eliminated, ensuring enduring clarity and certainty regarding its treatment within both current and potential future frameworks. By undertaking these actions, energy hubs can better contribute to network management.

7.6. Reflection on Limitations

This section reflects on the limitations for the different data gathering and analysis methodologies used throughout the these. Sections 7.6.1 explores the limitations encountered with the data gathering methodologies, and section 7.6.2 goes into detail in the analysis tools used.

7.6.1. Limitations on data gathering methodologies

Using a **literature review** to explore the key components and objectives of an energy hub has its limitations. The scope of the review may be limited, potentially missing out on recent developments and variations in definitions. The context-specific nature of energy hubs can also restrict generalisability. Additionally, biases, incomplete information, and a lack of consensus among researchers can impact the findings. To overcome these limitations, it is crucial to supplement the literature review with other research methods to obtain a more comprehensive understanding of energy hubs and incorporate real-world perspectives. This ensures a well-rounded analysis that captures the dynamic nature of energy hubs in practice.

When using **interviews** to answer the question of what makes energy hubs a successful tool in achieving policy goals important to the DSO, there are inherent limitations to consider. Firstly, interviews have their general limitations, such as potential biases, subjectivity, and variations in responses due to personal experiences or perspectives. Additionally, in this specific study, the interviews were conducted solely with individuals from Stedin, which limits the analysis to the perspective of one DSO. While Stedin's insights are valuable, a more comprehensive analysis could have been achieved by interviewing representatives from other DSOs, such as Liander and Enexis, to gain additional viewpoints and ensure a broader understanding of the topic.

When considering the limitation of not interviewing representatives from different DSOs, it is important to note that DSOs generally do not compete with each other and have a culture of sharing information and knowledge. This means that while the insights from Stedin provide valuable perspectives, there is a certain level of consistency and similarity in the approaches and challenges faced by different DSOs. However, including representatives from other DSOs in the interviews would have undoubtedly contributed to a more comprehensive analysis, considering potential variations in their policies, experiences, and perspectives.

The **information provided by Stedin** had certain limitations in addressing the question about the opportunities and threats presented by EHs to the DSO. As a non-Dutch speaker, the lack of fluency in Dutch slowed down the process of going through the documents provided by the company. Understanding Dutch law, which is already complex, became even more challenging without full proficiency in the language. Additionally, bureaucratic constraints within the company may have limited the extent of information that could be shared. However, despite these limitations, the information provided by the company still offered valuable insights into the practical aspects of EHs and their implications for the DSO. It is important to acknowledge that overcoming language and bureaucratic limitations would have provided a more comprehensive analysis of the opportunities and threats associated with EHs for the DSO.

7.6.2. Limitations on data analysis methodologies

Conducting an **actor analysis** for EHs presents certain limitations that should be taken into account. Stakeholder analysis can often be theoretical and challenging to generalize due to the varying interests of stakeholders based on location. Additionally, the analysis primarily focuses on two dimensions, which may overlook other factors that could provide valuable insights. Given the dynamic nature of stakeholder interests, a more extensive analysis is warranted, such as the use of surveys and questionnaires. This approach allows for a more comprehensive understanding by capturing characteristics that the stakeholder mapping, specifically the power-interest grid, may not fully encompass. By incorporating a broader range of perspectives and factors, a more nuanced and comprehensive actor analysis can be achieved, leading to a deeper understanding of the roles and interests of different stakeholders in the context of EHs.

The **SWOT analysis** encountered a few limitations in assessing how energy hubs can be used to achieve different goals. Firstly, the analysis heavily relies on the availability and accuracy of data and information, as the data gathering method for the SWOT analysis was interviews, therefore the same limitations are present here too. The quality and comprehensiveness of the data can impact the reliability and validity of the analysis. Furthermore, the SWOT analysis provides a static snapshot of the current situation and may not fully capture the dynamic and evolving nature of energy hubs. For example a lot of the threats highlighted in the SWOT analysis were about the unknowns of how the contracts will work, these will become more known as time passes. Another limitation is the potential oversimplification of complex factors into discrete categories. The SWOT analysis categorises factors into four distinct categories, which may overlook the interdependencies and complexities among different factors. This oversimplification can limit the depth of analysis and fail to capture the full complexity of energy hub dynamics. Lastly, the SWOT analysis is a qualitative assessment and does not provide quantitative measures or metrics. While it offers a valuable framework for identifying and categorising key factors, it may lack the precision and quantifiable insights necessary for rigorous decision-making and strategic planning. Considering these limitations, it is important to supplement the SWOT analysis with other analytical approaches and data sources to obtain a more comprehensive and robust understanding of how energy hubs can effectively contribute to reaching different goals. Considering these limitations, supplementing the SWOT analysis with the business case development for the Reimerswaal case study allows the analysis of the value added to also be qualitative.

Analysing **case studies** also has limitations that need to be considered. One of the primary limitations is the reliance on assumptions, which are necessary for conducting the analysis but may not reflect the actual real-world conditions. In the case of Reimerswaal, the analysis does not account for the efficiency gained from using residual heat generated by the electrolyser or explore the amount of hydrogen produced. Instead, it focuses solely on the impact of the electrolyser on grid capacity. Furthermore, the case study is not fully representative of the current situation, as it assumes the inclusion of all generation sources in the area for the electrolyser, however at the current stage no formal collaboration has been established. The ECUB case presents a significant limitation in that it is not an energy hub, rendering the analysis incomparable with the Reimerswaal case. These limitations highlight the need for careful interpretation and consideration when analysing case studies, taking into account the specific assumptions made and how representative of reality the cases are under examination.

8 | Conclusion

In conclusion, this thesis has effectively addressed the research question of how energy hubs can contribute to network management in the Dutch energy system. By comprehensively examining various aspects of energy hubs, including their definition, stakeholder analysis, theoretical and practical value, a comprehensive understanding has been achieved. The exploration of the definition of energy hubs has provided clarity and a common understanding, allowing for more precise project definitions and avoiding the indiscriminate use of buzzwords. The analysis of actors has shed light on their interests and roles, highlighting the importance of collaboration and identifying potential synergies. Furthermore, through the SWOT analysis and examination of case study projects, opportunities and limitations have been identified, contributing to a deeper understanding of the role of energy hubs in network management. Overall, this thesis has made significant strides in unravelling the complexities of energy hubs and their potential contributions to network management, providing valuable knowledge and actionable insights for both academia and DSOs.

A discussion of the academic value is provided in section 8.1, followed by a consideration of the value added to the company in section 8.2. Finally section8.3 identifies a topic of possible interest for future research.

8.1. Academic Value

By exploring the key components, objectives, and actors involved in energy hubs, it enhances the understanding of the intricate dynamics and complexities of these systems. The findings provide valuable insights into the design, operation, and management of energy hubs, contributing to the existing body of knowledge in the field of energy systems and network management.

Moreover, investigating the factors that make energy hubs a successful tool in achieving policy goals important to the DSO offers novel perspectives on the role of energy hubs in supporting sustainable energy transitions. The analysis of the opportunities and threats presented by energy hubs to the DSO contributes to the identification of potential challenges, risks, and mitigation strategies. These insights offer a deeper understanding of the implications and impacts of energy hubs on the grid and inform the development of effective strategies for network management and integration of renewable energy sources.

Overall, the academic value of the findings of this thesis lies in the advancement of knowledge, the generation of new insights, and the practical implications for sustainable energy transitions. It fosters interdisciplinary collaboration, drives innovation, and facilitates informed decision-making in the pursuit of efficient, resilient, and sustainable energy systems.

8.2. Value for the Company

The value for the company particularly lies in the bridging of knowledge gaps within the company, gaining a clear understanding of this new concept, and enhancing project definition.

Among the research questions, the third research question - ”What makes EH a successful tool in achieving policy goals important to the DSO?” brings the most value in terms of bringing knowledge from different departments together and bridging the gap between various perspectives (explored in section 5.3 and answered in section 7.3). This holistic approach facilitates a comprehensive understanding of the interdependencies and synergies between energy hubs and policy objectives. By examining the success factors, Stedin and other DSOs can leverage this knowledge to align their strategies, investments, and operational practices with policy goals, leading to effective policy implementation and outcomes.

Furthermore, having a definition of energy hubs derived from various academic sources offers DSOs a clear understanding of the academic meaning and implications of energy hubs (see section 5.1.1). This enables them to compare and align their existing understanding and use of the term with the academic consensus. By using a well-defined and comprehensive definition, DSOs can refine their project definitions, avoid using buzzwords without valid justification, and ensure a more accurate and consistent interpretation of energy hubs. This clarity and alignment enhance communication, collaboration, and decision-making within the organisation and with external stakeholders, facilitating effective planning and implementation of energy hub projects.

8.3. Future Research

An area for further exploration in the field of energy hubs is to conduct a comprehensive mapping exercise to determine where and under what conditions energy hubs are most applicable in the Netherlands. This research would involve examining various factors, including grid congestion levels and the characteristics of different customer segments in terms of their energy demand and generation capabilities. By mapping out locations that make the most sense for implementing energy hubs, valuable insights can be gained regarding the potential benefits and challenges associated with different areas. This research could contribute to the development of a strategic framework for identifying priority regions where energy hubs can effectively address grid congestion and optimise the utilisation of energy resources. Additionally, considering the diversity of customers and their energy profiles, such research would help determine the most suitable locations for energy hubs that align with the specific needs and capacities of different customer segments. Overall, this mapping exercise would provide valuable guidance for policymakers, grid operators, and stakeholders in making informed decisions about the deployment of energy hubs in the Netherlands.

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A | Appendix A - Interview Template

Name:
Date:
Location:

This interview is to gain insights into how energy hubs can be used as a tool to reach certain policy goals important to Stedin. In order to analyze these goals I will perform a SWOT analysis for each goal. The goals are:

Connect all requests to the grid Make better use of existing infrastructure Increase the share of renewable energy (in the dutch energy system)

Goal 1: Connect all requests to the grid (in a timely manner):

Strengths	
Weaknesses	
Opportunities	
Threats	

Goal 2: Make better use of existing infrastructure

Strengths	
Weaknesses	
Opportunities	
Threats	

Goal 3: Increase the share of renewables (in the Dutch energy system)

Strengths	
Weaknesses	
Opportunities	
Threats	

These are currently the candidates I have requested to interview, do you have anyone else in mind that would be interesting to include?

B | Appendix B - List of Interviewees

Date and Time of Interview	Position of the Interviewee in Stedin
June 19th at 15:30	Grid Strategist
June 21st at 14:30	Innovation Manager
June 22nd at 09:30	Lawyer
June 21st at 11:00	Proposition Manager Mobility
June 27th at 9:00	Flexibility Proposition Manager
June 30th at 11:30	Energy System Strategist
June 29th at 11:30	Electrical Transportation Advisor
June 28th at 14:30	Energy Transition Advisor
June 30th at 10:00	Strategic Advisor

C | Appendix C - Interview Notes

Strengths	Efficient use of capacity Currently what is driving EHs Realization of more connection requests and capacity
Weaknesses	Less control over components inside EH, that may affect the grid All flexibility stays within the EH Need for efficient management of the EH Scarcity of specialized manpower EH doesn't have to follow non-discriminatory policy May not be able to cope with all requests
Opportunities	Brings stakeholders together Customer engagement Insight into customer behavior facilitating grid planning Single point of contact facilitates communication Possibility for joint investments
Threats	Participants don't change behavior Aging of equipment Complex, and assumption DSO will organize Possibility for unfair grid fees Distance between DSO and individuals Risk of parties stopping their cooperation Difficulty of ensuring entity sticks to contract

Table C.1: Compilation of interview notes for goal 1: Connecting all requests to the grid

Strengths	Rfficient use of capacity Local operation
Weaknesses	Potential aging of equipment Sub-optimisation, may affect network outside EH Require specialized knowledge Complex design when multiple grid components are used
Opportunities	More space for companies to connect Increased adoption of innovative solutions Delay in grid reinforcement Conversion may enrich and improve energy system as a whole Well organized groups with more energy system knowledge and consciousness
Threats	Operating closer to the limit, leading to an increase risk of degradation of equipment leading to a reduction in flexibility and robustness, leading to less comfort for user behavior Risks associated with the collapse of the EH Sense of urgency for reinforcement investments removed

Table C.2: Compilation of interview notes for goal 2: Make better use of existing infrastructure

Strengths	Matching of local generation and consumption Allow for more connections, which increasingly come from RE
Weaknesses	Miss opportunity for economics of scale Adds dependabilities and uncertainty to the EH Necessity of buffers (batteries, electrolysers, boilers…) make system more complex and expensive
Opportunities	Make use of otherwise curtailed generation Energy system planning Allows for coordination between Municipalities' spatial vision and DSO's expansion vision Less energy losses through transportation Driver for change in development mindset Joint purchase of components
Threats	Harder for macro optimisation Uncoordinated development of EHs Ownership disagreements There are still unknowns of a 100% renewable system

Table C.3: Compilation of interview notes for goal 3: Increase the share of renewables (in the Dutch energy system)