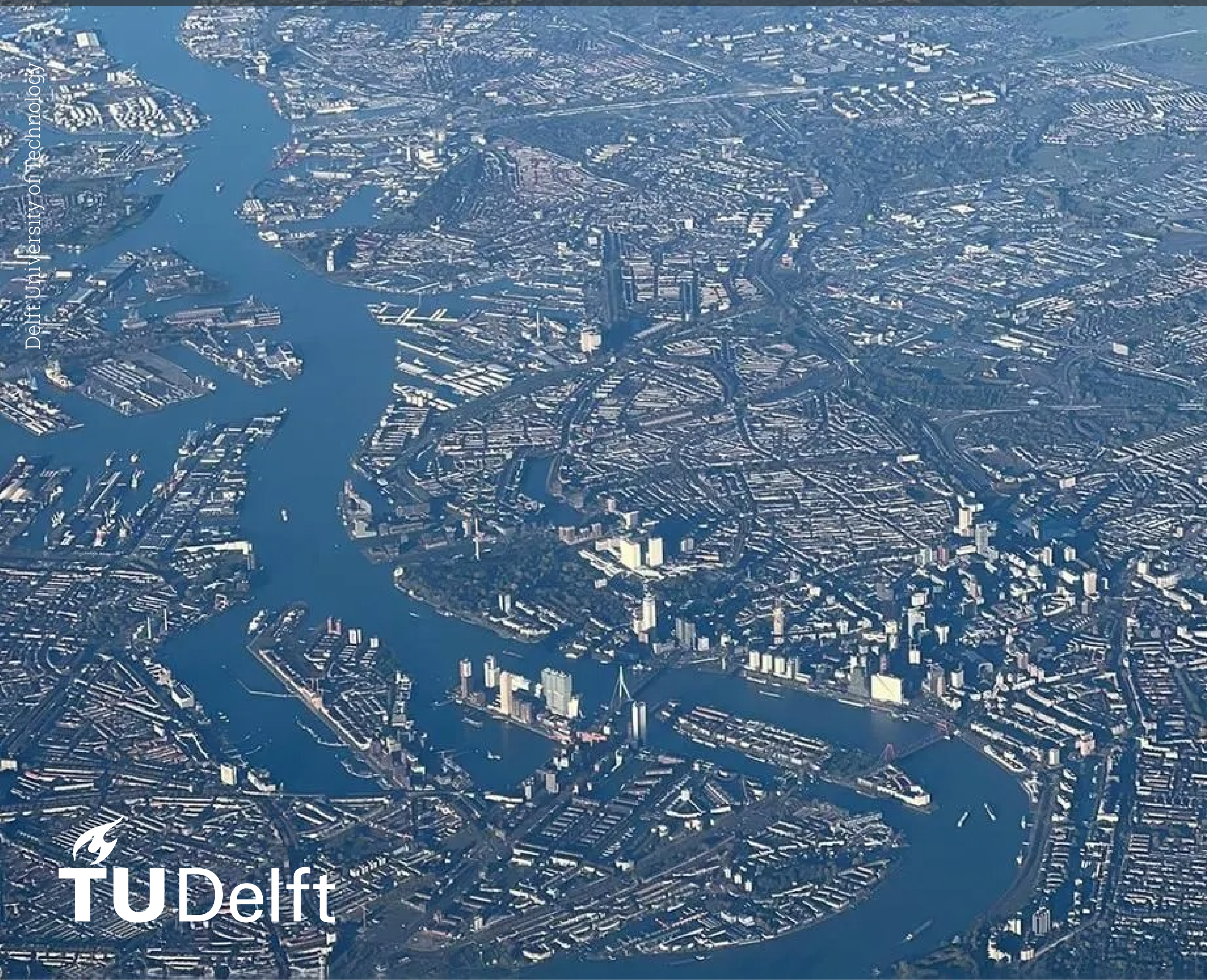
Energy Hubs for a Resilient Port Energy System

An Exploratory Modelling and Analysis Approach to Alleviate Grid Congestion in the HIC Rotterdam

Lennard Nathan Bal



Delft University of Technology

TU Delft

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An Exploratory Modelling and Analysis Approach to Alleviate Grid Congestion in the HIC Rotterdam

by

Lennard Nathan Bal

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Acknowledgements

Completing my master's thesis marks the end of my studies in Sustainable Energy Technology. In this final project I have been able to apply knowledge from all different aspects of my studies, from modelling to evaluating policy decisions. I feel lucky to have worked on a project that allowed me to incorporate all these different aspects. Applying EMA in my research forced me to adopt a new way of thinking about the future and has taught me a different approach to decision-making for system planning. In the process I have learned an incredible deal on energy system integration, as a solution to the many problems we are currently facing regarding the energy transition.

A large part of what I have learned I owe to the incredible New Business & Portfolio team of the Port of Rotterdam who have welcomed me as part of their team in the past eight months. I am very grateful for all the opportunities I have had to learn from their work during workshops, meetings, conferences and conversations, as well as the many invitations to enjoyable non-work related activities. I can say I am inspired by the people and all the different projects that are being worked on driving the energy transition in the Netherlands. A special thanks to Maike Akkers, my daily supervisor. I have felt welcomed into the team from the beginning and really appreciate the guidance while I was finding my way in this research project. Furthermore, I would like to thank the industry experts both within the Port of Rotterdam as well as from private companies who have provided me with their knowledge and insights.

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This thesis topic and approach are largely formulated by myself. Which has proved a more challenging task than anticipated beforehand. I am proud to have designed a project in which I demonstrated the execution of a research project at academic level while producing tangible results for the Port of Rotterdam.

I want to thank the reader for the interest in this work. Hopefully it contributes to adopting a different way of thinking about energy system planning and adds knowledge on the challenges faced regarding the energy transition and energy hubs as a potential solution. I hope you enjoy reading it.

Lennard Nathan Bal
Rotterdam, May 2024

Executive summary

In October 2023 congestion is issued in the HIC Rotterdam. As a result businesses can no longer establish, expand or electrify. A potential solution to free up grid capacity is that of an energy hub. This study evaluates future scenarios for the development of an industrial energy hub by utilising the EMA method. A study is done on the details of the congestion problem in the HIC Rotterdam in order to distinguish possible solutions. By exploring technologies applicable in an energy hub and applying exclusion criteria the potential for energy hub integration in the HIC Rotterdam is assessed. Based on the outcomes of a data inquiry a choice is made on an industrial cluster to model. Factors influencing the cluster's development in the future are drafted and scenarios are designed that describe the potential evolution of the cluster. The electricity system of the industrial cluster is modelled and its data analysed. The model of the electricity system is translated into a model that generates future states of the industrial cluster. Through EMA these scenarios are evaluated.

The congestion problems faced in the HIC will last until project 'Loadpocket Simonshaven' is commissioned in 2027-2029. Until then, energy hubs might be valuable in creating grid capacity. Making shared use of an electricity connection can already create some extra capacity, however the implementation of large electrification projects is most influenced by the availability of additional grid capacity. As becomes clear from the simulation results. In addition, a promising integration option is the inclusion of an electricity generation unit in the energy hub of which multiple exist in the HIC Rotterdam.

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Nomenclature

Abbreviations

Abbreviation	Definition
AC	Alternating current
ACM	Authority for Consumers and Markets
AFIR	Alternative fuels infrastructure regulation
ATO	Connection and transmission agreement
BESS	Battery energy storage system
CAES	Compressed air energy storage
C-CBC	Collective capacity limiting contract
CESA	Continental Europe Synchronised Area
CDS	Closed distribution system
CHP	Combined heat and power
CO_2	Carbon dioxide
DC	Direct current
DER	Distributed energy resources
DLR	Dynamic Line Rating
DR	Demand response
DSM	Demand side management
DSR	Demand side response
DSO	Distribution system operator (i.e. Stedin)
DWT	Deadweight tonnage
EMA	Exploratory modelling and analysis
EMS	Energy management system
ESS	Energy storage system
EU	European Union
EV	Electric vehicle
FACTS	Flexible AC transmission system
FC	Fuel cell
FTE	Full time equivalent
GDP	Gross domestic product
GHG	Greenhouse gas emissions
GTO	Group transmission agreement
GW	Gigawatt
GWh	Gigawatt hour (unit of energy)
HIC	Harbour industrial complex
Hz	Hertz (unit of frequency)
H_2	Hydrogen
IDE	Integrated development environment
KNMI	Royal Netherlands Meteorological Institute
kV	Kilovolt (unit of voltage)
LAN	National Grid Congestion Action Program
LDC	Load duration curve
MVA	Megavolt-ampere (unit of apparent power)
MW	Megawatt (unit of power)
MWe	Megawatt electric (unit of power)
NDC	Nationally determined contributions
PRIM	Patient Rule Induction Method

Abbreviation	Definition
PV	Photovoltaic
P2G	Power-to-gas
P2P	Peer-to-peer
P2X	Power-to-X (X representing any energy carrier)
RAM	Random access memory
RDM	Robust decision making
RES	Renewable energy sources
SGV	Sea-going vessel
SNG	Substitute natural gas
TEU	Twenty-foot equivalent unit
TSO	Transmission system operator (i.e. TenneT)
TW	Terrawatt (unit of power)
TWh	Terrawatt hour (unit of energy)
VPP	Virtual power plant
VRU	Vapour recovery unit
V2X	Vehicle-to-X (X representing any electric load)

Symbols

Symbol	Definition	Unit
E	Energy	[J or Wh]
f	Frequency	[Hz]
g	Coincidence factor	[-]
I	Current	[A]
P	Power	[W]
U	Voltage	[V]
ρ	Density	[kg/m^3]

1 Background

1.1. Introduction

With emission reduction targets coming closer, industries are more and more transitioning towards sustainable use of energy. The transition to a sustainable energy system is believed to develop along four pillars; efficiency improvements, electrification, a switch to green molecules and carbon capture [33]. These pathways all follow different timelines. The transition to green molecules and use of carbon capture are still in their early stages and not yet matured sufficiently to service entire industries. On the other hand, efficiency has shown to follow continued improvements in the last decades. Up to the point where the Netherlands' energy consumption is currently lower than it was in 1990 [39]. The second pathway, electrification, is picking up speed. Different sectors show varying progress as the Netherlands is second only to Australia concerning solar panels per capita and one of the global leaders in realising charging infrastructure for electric transport. Industry is starting its electrification process as companies are moving away from natural gas and building electrolysers and e-boilers. Many of the electrification efforts have been further accelerated by the high gas prices resulting from the war in Ukraine. This acceleration is well illustrated by the projected growth in electricity use in the Rotterdam port area; the growth originally anticipated from 2020 to 2030, has already been requested in the years between 2020 and 2022 [69]. Accelerated growth in combination with the mismatch between lead times for electrification projects and grid expansion projects, where grid expansion typically takes years longer to complete, has cascaded to congestion being issued in almost every part of the Netherlands.

To tackle the problem of grid congestion solutions are structured along three pillars; faster expansion, better use of the available infrastructure and the development of flex capacity. The latter solution can be developed through various concepts of which the energy hub is a new and innovative example. The problem of grid congestion is caused by an accumulation of factors regarding multiple stakeholders. An energy hub requires cooperation between multiple players. Therefore, an overarching organisation is quintessential in the success of this solution. For the HIC Rotterdam the Port of Rotterdam is well-positioned to guide this process.

The proposed research project will employ a mixed-method approach featuring an explanatory design aimed at finding characteristics for an industrial cluster that help the implementation of an energy hub. This challenge involves both technological components in the optimal planning of energy hub operation as well as financial and governance components. This makes it highly complex, which is further exaggerated by the number of stakeholders needed to successfully realise an energy hub. This research however will focus on the technological aspects and touch upon other aspects whenever these might be influential. The results of this research will be beneficial to the port authority and industries located in the HIC, as well as grid operators. Energy hubs can be utilised to reach climate goals and industries can benefit from improved efficiency and lowered costs. The thesis project is carried out in close co-operation with the Port of Rotterdam, the port authority responsible for exploiting the largest harbour industrial complex in Europe. By using representative data and considering actual use-cases it allows for the research to learn from and be directly applicable to real-world situations.

The topic of grid congestion is relatively new in the Dutch public debate, with an even newer addition being the concept of the energy hub. This background chapter serves to shed light on the complexity of the congestion issue, relevance of this research and help the reader to better understand the contents of this report. An outline of the Dutch electricity grid is provided in Section 1.2. Subsequently, the concept of an energy hub is explored to establish the necessary framework for the thesis in Section 1.3. Lastly, Section 1.4 provides an introduction to the Port of Rotterdam, since this will be the area of focus for this research.

1.2. Dutch electricity grid

The first public electricity supply in the Netherlands was commissioned over a century ago. Over this time it has developed to its current state. Currently, the grid and its operators are under societal pressure to quickly reform to swift changes in demand. Changing electricity needs and how these result in grid congestion are presented in this section. Grid congestion is one of the main reasons for starting this research. To better understand the motivation behind this research, grid congestion is further elaborated. Solutions to grid congestion are presented as well. Lastly, a discussion on the continued need for flexible electricity use is presented. An extension on the background on the Dutch electricity grid including its historical development and grid issues resulting from the energy transition other than grid congestion, please refer to Appendix A.

1.2.1. Energy system in transition

A prerequisite for facilitating these market freedoms is an abundance in grid infrastructure. A recent surge in electricity demand caused by electrification efforts challenges this infrastructure abundance, putting the 'copper-plate' principle to the test. The electrification efforts originate from the ambitions expressed in the various climate agreements. In 2015 the Paris Agreement was adopted as a successor to the Kyoto Protocol from 1997. The Paris Agreement introduced judicial support for limiting global warming to a 2°C increase. It also required member states to set nationally determined contributions (NDCs) and describes the expectation of developed countries to financially support emissions reduction efforts of developing countries. To align European policy with the set ambitions, the Fit for 55 package is constructed. This package presents a roadmap to reduce greenhouse gas (GHG) emissions in the EU by 55% in 2030, compared to 1990 emissions levels. The Netherlands, as EU member state, are thus striving for a 55% reduction as well. Apart from reducing and reusing energy, and switching to alternative fuels, transforming electricity generation and electrification will contribute largely to emissions reduction.

The electricity demand is projected to grow from 120 TWh/y currently to approximately 200 TWh/y in 2030 [162]. The industry in the Netherlands, the largest consumer of energy, is estimated to increase its electricity demand by 80-130 TWh in 2050, compared to current consumption. This amounts to three to four times its current electricity consumption. This means that in addition to the replacement of fossil energy generation, the generation capacity needs to scale up as well.

Until now, power grids have operated as a load-driven system. The basic idea behind this is that loads are predictable, even though only in a statistical sense. Thanks to this statistical prediction, generation is scheduled. The error in predictions are compensated by peaker plants. Such an approach is possible, assuming that generation is fully controllable and concentrated in large power plants, so that the scheduling problem is solvable. In the new scenario, we are moving more and more towards a generation-driven power system, where generation leads and the rest of the system follows. This is due to the intermittent characteristic of wind and solar power. With an increasing role of dynamics and the need to operate grids closer to their limit, this new scenario is creating the need for new solutions and technologies.

1.2.2. Issues resulting from the energy transition

Though the transition to a renewable generation-driven power system is theoretically possible, it is complicated by multiple factors. One of the main challenges grid operators are facing is the mismatch between the speed in which the energy system is developing and the lead times necessary for grid reinforcement projects. On the consumer side examples of projects are the installation of heat pumps, solar PV or electrification of industrial process, which respectively take months, a year and about four years to complete. Grid reinforcements projects for these respective projects however require a year, three years or up to 10 years to complete [134, 144].

This mismatch requires grid operators to think ahead in terms of grid planning and to finance pre-investments into grid reinforcements. Yet, in the years leading up to the energy transition the investment policy of the grid operators remained overly focused on cost efficiency. This policy, which was sustained by the lack of incentive provided by supervisory authority ACM, led up to a false start for the energy transition in the Netherlands as concluded by [63, 120, 168].

In the 20's of the 21st century the efforts needed to make the energy transition a success started to be recognised. Grid operators now doubled their annual investments compared to 2019. Though this financial boost helps in facing the transition challenge, scarcity in terms of personnel, equipment and physical space to build cables and stations limits progress [85]. Consequences of this delayed transformation of the power system is a congested electricity grid with severe consequences for society as a result, as described by the Dutch Minister for Climate and Energy Policy Rob Jetten in his letter to the President of the House of Representatives after TenneT published congestion studies for the regions Utrecht, Gelderland, Flevopolder and the HIC Rotterdam [73].

Initially, congestion occurred when supplying the grid with electricity in rural areas with distributed electricity generation (DER), such as wind and solar farms. These DER systems differ significantly from traditional centralised energy generation methods, such as gas turbines and nuclear power plants, which have historically supplied our energy needs. Unlike these centralised sources, RES are inherently decentralised. This decentralisation introduces a challenge, as the existing electrical grid infrastructure was originally designed to accommodate the efficient transmission of energy from large power plants through robust power cables to various industrial and urban centres. In contrast, onshore wind and solar farms are often situated in rural areas that lack adequate electricity infrastructure. In addition to the expanding adoption of solar PV systems and onshore wind farms, the Dutch government is driving the development of offshore wind farms in the North Sea. The target for 2023 is to establish a minimum offshore wind power capacity of 4.5 GW. Looking further into the future, the government has set ambitious objectives. Currently, the government is working to achieve 21 GW by 2030 and aspires to reach 70 GW by the year 2050 [72]. Consequently, the grid's historical configuration has become ill-suited to accommodate the changing landscape of decentralised energy generation.

In 2022 energy prices skyrocketed as a result of sanctions against Russia following its invasion of Ukraine. Suddenly, electrification of processes that were previously deemed too expensive became a fitting solution to cope with high fuel prices. The industrial sector, already looking for decarbonisation options to adhere to increasingly strict emissions legislation, seized the opportunity to accelerate decarbonisation by switching to electrically driven processes. As a result, in 2050 an estimated 60% of the energy need from the industry will be electric. Towards 2050 the annual dutch industrial electricity demand will grow by 80-130 TWh just from electrification alone. This means that between 2021 and 2050 the industrial electricity demand will grow 3 to 4 times in size [126]. Without sufficient mitigation strategies the 'copper-plate' principle will be pushed to, and at times possibly over, its limits.

1.2.3. Grid congestion

The term grid congestion is a hot topic in the Netherlands at the time this report is written. An increasing amount of projects throughout the country are getting delayed or postponed indefinitely due to grid congestion. The state of the congestion problem in the Netherlands is displayed at the Capacity Map which is provided by the grid operators and can be found at [116]. During the conduct of this research the map has become increasingly red, until the point where the majority of the Netherlands is labelled as congestion area. In this report the term is mentioned multiple times already as it formed the reason for starting this research by the Port of Rotterdam. To increase the understanding of the subject and better understand the context of this research an explanation on the topic is provided.

Congestion can best be explained by an analogy on traffic. The road network resembles the electricity grid and cars on the roads resemble electricity. Most of the day cars can travel from A to B without any problems. During peak hours however too many cars need to pass over a certain road surpassing the road's transport limits, causing a traffic jam. This traffic jam is similar to what happens during grid congestion, more electricity needs to pass certain infrastructure elements than what their limits allow. A crucial difference between traffic and electricity is that cars will be delayed following a traffic jam, however due to electricity's inherent characteristic where it is consumed instantly, in the case of congestion the surplus electricity is simply not delivered.

It is important to understand that congestion is not caused by a deficit in electricity production but rather a shortage of grid infrastructure to transport electricity from point A to B. Grid infrastructure encompasses all infrastructure necessary to transmit electricity, such as power cables and transformers. Contrarily, imbalance is the phenomenon where production does not equal consumption. While flexibility in electricity demand can also be used to mitigate imbalance it is a different application than congestion management. More so, activation of balancing services can actually increase congestion problems. As an example, imagine the case where a power plant in the East of the Netherlands suddenly fails. Since the Netherlands is not subdivided in bidding zones a power plant in Rotterdam can increase its production capacity to meet the deficit in power caused by the failing power plant. However if the power cable between these two locations was already operating near maximum capacity, the extra transmission of the necessary balancing power will cause a congested power cable.

It is argued by some that the electricity grid in the Netherlands currently is not congested, but rather faces a deficit in transmission capacity. This is technically accurate, as currently power cables in the Netherlands do not see any failure do to overloads. The term congested is intended to indicate the likeliness of overloads if all demand projections are to be realised. Current capacity would then be insufficient to transmit the necessary electricity volumes. The way grid operators make predictions about the future state of the electricity system is based on a few factors. Currently measured electricity load, autonomous growth assumptions and new connection requests. If the combination of these factors result in capacity limits being reached before expansion projects can be realised, congestion is issued by the grid operators.

1.2.4. System solutions

In a response to the issued congestion by grid operator TenneT in multiple parts of the country, the Dutch Minister for Climate and Energy Policy has proposed a set of solutions [73]. When applied to the industrial sector these solutions align with the three main objectives of the National Grid Congestion Action Program (LAN in Dutch) [85]; build faster, better utilisation of the power grid and flexible use of the grid.

Build faster

As described in both documents the expansion of the grid is a 'no-regret-option'. Grid expansion typically takes seven years which, due to the high demand of connection requests, causes accumulation of parties on grid operators' waiting list. A large part of this lead time is however wasted on acquiring the necessary land and permits. The Ministry aims to facilitate in this process by taking charge of the land acquisition and permit process.

Better utilisation of the power grid

Making better use of the grid is the next solution presented by the Ministry. Important to note is that congestion is a temporal phenomenon. Due to the inherent properties of the electricity grid overloads can cause immediate faults, however congestion typically only occurs for a few hours throughout the year. The power grid must therefore be dimensioned to handle peak demand. Congestion management is a prominent solution facilitating better use of the available capacity. Congestion management is the reimbursement by grid operators for companies altering their operation schedule. Companies who are able to apply demand side response (DSR) strategies like peak shaving, load shifting, load curtailment or valley filling can receive compensation for their efforts in order to alleviate the grid. Multiple forms of flexibility contracts exist that provide economic incentives for flexible use of the grid. Individual Connection and Transmission Agreements (ATO in Dutch) can in the future be replaced by Group Transmission Agreements (GTO in Dutch) or non-firm ATOs; contract forms still being developed that help in balancing electricity consumption locally [117]. These are all solutions that come with a price. Aforementioned solutions are economic options, there are however certain cost-free technical solutions available to alleviate grid congestion [47]. Examples are the modification of the system topology, installing transformer taps, installation and application of various types of controllers, e.g. FACTS, or capacitor banks, dynamic line rating (DLR) or strategically utilising buffer capacity [173, 34].

Flexible use of the grid
The first two solutions describe efforts that can be taken by the grid operators. The third solution, 'create flexibility in electricity demand', looks at industries to help combat the problem. A solution that is often suggested by literature and business papers is to include flexibility in the form of Battery Energy Storage Systems (BESS). These systems can rapidly and reliably inject or withdraw power through electrochemical conversion, allowing them to participate in imbalance markets. However, employing a BESS in imbalance markets aggravates the congestion issue. Considering both the advantages and disadvantages, this multi-functionality leads TenneT to regard BESSs as 'net-neutral' in their calculations (personal communication, 2023).

More promising solutions regarding flexibility are found in the utilisation of demand side response (DSR). Heavy electricity loads can potentially be rescheduled thereby providing flexibility to the grid. The grid can then be locally alleviated to allow for increased use on moments of lower demand. A rather new concept creating flexibility that is being explored is the energy hub. In the letter to the President of the Dutch House of Representatives, Minister for Climate and Energy Policy Rob Jetten mentions an incentive program worth €166 million will be made available for the development of energy hubs in the Netherlands.

1.2.5. Future need for flexibility

Though investments in flex capacity or energy system integration are often expensive enterprises that might seem troublesome for individual businesses, flexible system solutions are not only desired on short-term. The need for flexibility is urgent, however the dependency on unpredictable intermittent energy sources makes flex capacity required in the future as well. The increased electricity demand in combination with large shares of landfall from offshore wind complemented by solar farms in the Netherlands makes that flexibility will remain a desired asset in the future. The integration of energy systems into energy hubs will therefore have its added value both on the short and long term, increasing its value.

1.3. Concept of an energy hub

It is not yet clear what the exact definition is of the type of energy hub for which the Ministry has made subsidy available, as the term 'energy hub' can be used for a variety of applications. In academic literature it is described as an energy system that contains production, conversion, storage and consumption. A diagram showing a general structure of an energy hub is shown in Figure 1.1. In this section the reason for starting an energy hub and finally the definition adopted for this research are described. Additional information on the concept of an energy hub including its origin, technical features, scope, control systems and concepts similar to that of an energy hub are described in Appendix A.

1.3.1. Benefits and challenges

To understand the concept of an energy hub, the goal behind one should be understood as it is fundamental to its creation. Without an intended purpose, an energy hub will never originate. A list of reasons to develop an energy hub is given below [136]:

1. Align with sustainability targets
2. Facilitate electrification initiatives
3. Reduce necessary investments in grid reinforcements
4. Cut electricity costs through reduced demand and system services (flex/balancing)
5. Leverage economies of scale in infrastructure investments
6. Make optimal use of RES
7. Recycle waste streams (e.g. residual heat)
8. Security of energy supply
9. Increase certainty in investment decisions by having ownership of energy supply and demand

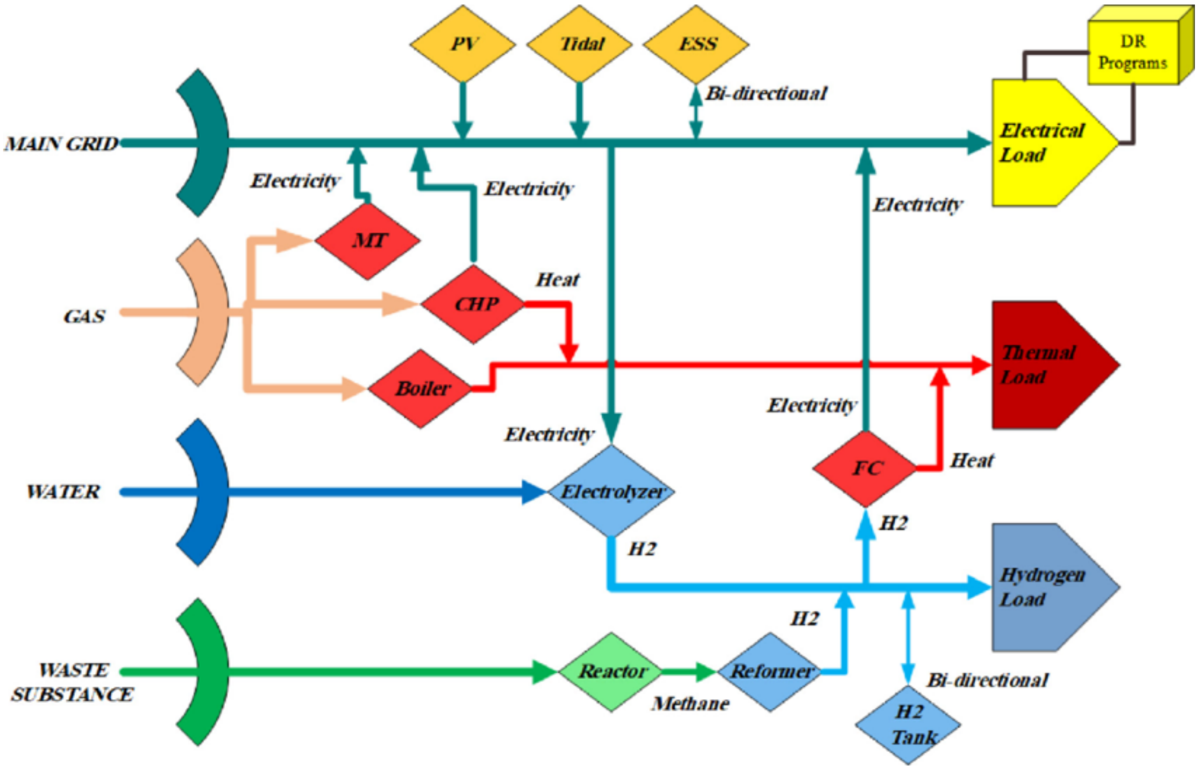


Figure 1.1: Diagram of a general energy hub configuration [188]

Each of the aforementioned motives can be a reason to research the possibility for an energy hub. Often, a combination of several of these motives form the catalyst to start a feasibility study. Unfortunately, there's no such thing as free lunch. The realisation of an energy hub presents a host of challenges, across various disciplines, all of which need to be overcome to ensure successful implementation [127].

Conflicts between parties might arise in the design phase; when negotiating on the parameters to be optimised one party might want to focus purely on minimising operational costs while an other might want to focus on emissions reduction due to enforced climate targets. Moreover, difficulties might arise when discussing the financial commitments each party will make. In a flexible interconnected system it might not be clear who benefits from the investments by how much. Therefore agreeing on investment responsibilities can be a tedious discussion. The same holds for ambiguous revenue streams such as direct sales, reduced operational costs, subsidies or emission permits. These imbalances and dependencies make deciding on a governance structure a complex task [61]. Companies themselves name a lack of cases and business models together with regulations on functionalities and operation as barriers to start an energy hub.

Capital intensive infrastructure is required to connect and convert energy flows between companies [113]. Control systems needed to regulate the energy flows are complex due to the uncertain behaviour of RES and subsequently market prices [101]. On top of that, companies are hesitant to share data necessary for the control of the energy hub with their neighbour as data might be market-sensitive [82].

Even when an energy hub is successfully established, challenges remain. One of the problems is the vulnerability imposed by the integration of the energy systems. When a company falls out of a collaboration, other parties might be left with a gap in their supply chain [91]. To keep the interconnected system in balance a company with a similar industrial process needs to take its spot. This creates a tight window for the site to negotiate with interested parties. If the presence of this barrier results in older industries being favoured over emerging clean industries seeking to establish themselves, it raises the question of whether the system integration itself may be hindering innovation [25].

Further drawbacks from an energy hub concerns grid operators. Currently, grid operators perform load flow calculations based on measured loads, assumptions on autonomous growth and new connection requests as explained in Subsection 1.2.3. An important parameter in this calculation is the coincidence factor. This factor is described in 1956 to indicate the simultaneity between peak loads and is introduced to account for the fact that connected customers do not require peak capacity at the same time during the day [128]. The formula for the coincidence factor is presented in Equation 1.1. For industry parties a value around 0.8 is generally chosen. The inclusion of this factor makes that more capacity can be issued than can theoretically be transmitted. The problem that arises when companies start to balance their loads in an energy hub is that their simultaneity changes.

$$g_n = \frac{P_{max,n}}{\Sigma_{i=1}^{n} P_{max}(i)} \tag{1.1}$$

1.3.2. Adopted definition

Different concepts regarding system integration get labelled with the term 'energy hub', examples are discussed in Appendix A. To place this research in the right context the adopted definition for an energy hub in this research is as follows:

A smart energy system enabling actors to locally coordinate the production, conversion, storage and consumption of multiple energy carriers

1.4. Port of Rotterdam

The Port of Rotterdam is the port authority for the HIC Rotterdam. In this area the port accommodates approximately 120 industrial companies representing diverse sectors and activities. An overview of the different industrial activities in the port is shown in Figure 1.2.

Where the primary goals of the seaport used to be focused on growth the Port authority sees a shift in ambitions over the last years. The Port of Rotterdam's purpose statement reads:

'Connecting the world. Building tomorrow's sustainable port.'

highlighting the focus on sustainability. The purpose statement is enforced by the large amount of innovative projects in the port. The utilisation of waste heat, carbon capture and storage, hydrogen infrastructure, wind energy landfall, an electrolyser park, biorefineries and shorepower are some of the innovative projects that help transform the port to a sustainable industry cluster.

Some of these innovative projects are currently facing challenges due to limited electricity supply in the area. Especially projects with a high electricity demand such as shore power are hampered by congestion issues. The wide diversity of industries located in the HIC, and with them a variety of energy flows, makes the area highly suitable for smart flexible energy system solutions. Innovative energy system integration solutions can pose solutions to the current congestion problem as well as be valuable knowledge development for the design of our future energy system.

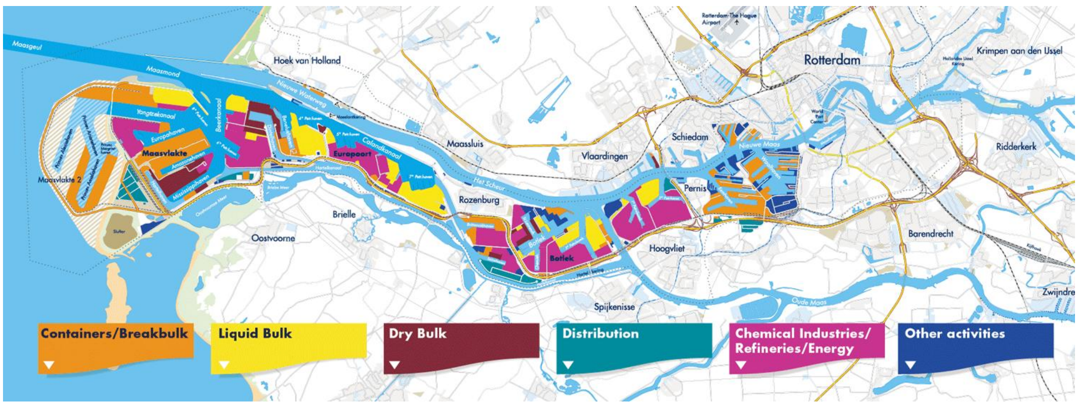


Figure 1.2: Map of industrial activities in the Rotterdam port

2
Literature review

In the previous chapter a background is presented on the topics that are fundamental to this research. The goal of this chapter is to explain the knowledge gap that will be supplemented by this research and the search that led to this knowledge gap. Section 2.1, dives into the themes within the topic of energy hubs relevant to this research. To extend the knowledge gained from literature with recent updates from the industry business reports are consulted as well. Especially on the topic of energy hub developments in recent years in the Netherlands as well as globally. The review on academic and business literature results in the identification of a gap in knowledge. This knowledge gap is discussed in Section 2.2, together with this research' contribution to the literature and research questions following from the identified knowledge gap.

2.1. Literature discussion

Chapter 1 provided an extensive introduction on the energy hub concept. The motivation for this research comes from the grid congestion problem faced in the HIC Rotterdam. Therefore, the literature review focuses on congestion management through the implementation of an energy hub. A search string is developed to find articles that apply an energy hub or related energy system integration solutions to find an answer to grid congestion.

There are multiple approaches that can be adopted when designing future systems. One of these is exploratory modelling. The literature reviews was extended by articles applying robust decision making under deep uncertainty to the energy hub concept. The different topics that logically followed from the literature search are shown in Table 2.1. Clear is that a gap exists in literature that includes uncertainties regarding the system environment when testing solutions for congestion relief.

Table 2.1: Comparison of reviewed literature

Article	Energy hub	Congestion	Changing energy sector
[49, 7, 48, 78, 99, 92, 146, 95, 189, 74, 185, 157, 98, 175, 94, 41, 153, 135, 140]	✓		
[64, 8]		✓	
[148, 190, 186, 191, 67, 45, 71, 96, 56, 164, 24, 165, 152]	✓	✓	
[106, 76, 4, 111]	✓		✓
Proposed research	✓	✓	✓

2.1.1. Literature themes

From the reviewed literature there seem to be three main motives that drive the research on energy hubs. The first one is the integration of distributed energy resources (DER), which focuses on optimal utilisation of the RES and hereby often reducing emissions. The second motive is economic efficiency, which is achieved by optimal utilisation of the available assets. The third motive is the deployment of energy hubs to mitigate congestion, either in the gas or electricity grid. The objective of this thesis project corresponds to the application of energy hubs to alleviate congestion in the electricity grid. This review is therefore focused on this last application. While performing the literature review answers resulted in new questions in a step-wise manner. This process, which eventually led to a gap in the academic literature as well as practical knowledge is described below.

Energy hubs

The concept of an energy hub has been first defined in the VOFEN project by Geidl et al. [50]. Before this project scientific studies used to investigate future scenarios based on boundary conditions given by today's structures. Although these studies provide valuable insights, they often result in solutions that comply with the existing systems; possibly interesting and more long-term oriented solutions are hidden, as they lie beyond system-given boundaries. To break with this tradition the "Vision of Future Energy Networks"-project (VOFEN) was initiated at ETH Zurich. It aimed at a greenfield approach for future power systems, applying a horizon of 30-50 years. In 2006 they published their research titled 'Energy Hubs for the Future' sparking the start of energy system integration.

Initially, applications of an energy hub focused on improving system efficiency in a fossil-fuel based generation system. With the introduction of DER the energy hub found a renewed purpose. Patterns of production and consumption not aligning results in renewable energy being curtailed at times and supplemented by the grid at others. Especially wind and solar energy tend to cause congestion, according to Hobbie et al. [64]. The majority of literature is thus focused on increasing renewable energy generation utilisation [92, 146, 95, 189, 74, 185, 157, 148, 190, 186]. Minimal CO_2 emissions through the use of renewable energy generation is researched in [98, 175, 94, 24, 41], among others.

Innovations in energy system technology lead to an increasingly diverse energy generation portfolio. Creating flexibility that can not only be exploited for minimum curtailment of DER, but for general economic efficiency within energy systems as well. [153] publishes the innovative idea to use the natural gas grid as storage medium for excess electricity. A combination of electrolysis, forming substitute natural gas (SNG), and a gas turbine created bidirectional energy coupling. Such a system is able to utilise whichever energy carrier is most easily available [135]. Currently, market forces push businesses to make optimal use of the available energy grids. Paving the way for a flexible industrial sector.

Congestion

As this research focuses on evaluating the energy hub concept as a solution to grid congestion the literature review was narrowed to energy hubs applied in a congested grid. Congestion is generally defined as a situation where the transmission systems are operated at or beyond their transfer limits [8]. Many articles discussing the integration of DER or efficiency improvements through energy hubs do not include constraints on electricity supply. While the grid used to be perceived as a 'copper-plate' its compromised state makes that grid constraints need to be taken into account fur future system planning. A research that focuses on the effects of system integration on grid congestion is presented in [56]. This project compromised resolution by applying a cellular approach in order to model the grids as accurately as possible within a reasonable computational time. [164] focuses on mitigating branch overloading and bus-voltage limits using P2G storage and compressed air energy storage (CAES). The study concludes that P2G and CAES pose viable solutions in relieving grid congestion. What aforementioned articles have in common is that they operate from the grid operators' perspective. The focus of this thesis project is different however as the aim is to open up grid capacity to support industrial activity in the context of a congested electricity grid. A similar approach on grid congestion is used in [111] where a consumer-oriented optimisation is applied. Mittelviefhaus et al. state that such an optimisation can guide consumers' decision making, which in turn is crucial for effective climate change mitigation. The belief that consumers are instrumental to a successful energy transition is shared and thus a similar orientation is adopted. A method to apply this perspective on congestion in an industrial context is developed throughout this research. Where Mittelviefhaus et al. capture the uncertainty of a changing energy sector by testing four different scenarios, this research adopts a more holistic approach.

Changing energy sector
In the field of energy system planning the importance of robust decision-making has grown as a result of the energy transition. While the 'copper-plate' principle used to be the foundation of our grid policy it is becoming less obvious, reinforcing the need for robust energy policy. A policy method that is tailored for robust decision-making is exploratory modelling and analysis (EMA) due to its ability to assist in reasoning about systems with significant uncertainty. Problems may arise when a model is built by consolidating estimations on future behaviour into a single package and then assuming it as a reliable image of a target system, this can be called predictive modelling. Exploratory modelling in contrast is the use of series of such computational experiments to explore the implications of varying assumptions and hypotheses. Bankes described this method of policy analysis in 1993 [14].

Seldom do articles discuss the effect of uncertainties related to the future energy grid configuration, let alone how to ensure robust planning decisions. An example that does is presented in [106], where effects of a changing environment on costs for DER are examined by introducing probabilistic model parameters. Articles on stochastic programming mention it is often difficult to obtain probability distributions for uncertainties [86]. Another downside to this predictive approach is that due to long lead times and the system's changing environment, parameters that influenced the investment decision might have changed by the time the project is finished. Hereby risking the chance of building infrastructure that does not meet future needs.

An even bigger limitation of predictive modelling arises when a 'best-guess' of the future system state can no longer be made. This is the case in an uncertain future where multiple plausible futures might exist. Uncertain drivers concerning climate, technological or political change might result in distinct futures for which no probabilities can be assigned or even ranked. When designing scenarios for a future system associated with deep uncertainty such as the energy system a different approach that does not depend on probabilities is needed. Consideration of multiple plausible futures can be done through the use of a scenario approach [100].

An example of a project that has adopted an approach where a scenario space is constructed in order to develop a robust adaptive planning strategy is the Gridmaster project, performed in collaboration with the Port of Rotterdam [184]. In this project the entire HIC Rotterdam was included in the scope. This research adopts a finer scope in the hope to develop a faster design process with even better traceable outcomes while still producing valuable results. Furthermore, in contrast to the regularly applied grid operators' perspective a consumer-oriented optimisation is applied, similarly to [111], though now in an industrial context.

2.1.2. Current state of energy hubs
Many articles on energy hubs research theoretical energy hubs in order to determine potential economic or environmental benefits. In these cases empirical data is used on, for example, wind speeds for power generation by wind parks, conversion efficiencies and demand patterns. Little knowledge is yet gained on the resulting increased capacity within a congested area when implementing an energy hub. To be able to construct a model that can help in evaluating planning strategies in a real-life context the current state of energy hubs worldwide and especially in the Netherlands is researched as final part of the literature review. It should be mentioned that most of this information comes from business reports or news articles rather than academic articles.

Energy hubs worldwide
The fact that little knowledge is yet gained on energy hub implementation can be partly attributed to the little amount of energy hubs yet developed in the world. The VOFEN project by Geidl et al., where the energy hub concept originated, inspired a municipal utility company in Switzerland. The Regionalwerke AG Baden pioneered the implementation of an energy hub by building an installation that obtained both natural gas and heat from burning wood chips. The natural gas could be pumped into the gas grid or converted into electricity through a cogeneration unit (CHP-system) and integrated into the electrical grid [36]. This example remains one of the few energy hubs mentioned in literature as is affirmed in [138], describing a knowledge gap regarding the impact of utilising energy hubs.

When stretching the term 'energy hub' beyond the identified scope of this research to include examples of industrial symbiosis, virtual power plants or other closely related concepts, integrated energy systems seem to pick up interest worldwide. More examples of multi-energy systems are found in Switzerland, Australia, the United States and England though most of these focus on residential or commercial applications. Examples of industrial symbiosis are described in [142] showcasing 20 industrial clusters in various stages of development. Location, market access and access to renewable or low carbon energy are described as three prerequisites for a successful operation, properties that can all be fulfilled in an industrial cluster. Moreover, it is stated that decarbonisation goals in particular are more easily achievable in a collaborative environment. An organisation that can take a neutral lead is essential in the development of such a collaboration, as well as political support. Interestingly, 17 out of 20 clusters are port-anchored, suggesting port authorities are well suited to take on this vital role in the development of collaborative industrial clusters. The Port of Rotterdam is not described in this report though it does feature multiple forms of industrial symbiosis which are extensively discussed in academic literature [11, 9, 12, 10]. Interconnections between plants exchanging steam, electricity or chemicals can be found on multiple locations throughout the HIC.

Energy Hubs in the Netherlands
When searching for developed energy hubs in the Netherlands the same conclusions can be drawn as on a global scale, they remain relatively scarce. Therefore, the research is extended to include other forms like industrial symbiosis, which shares similarities but is not identical to an energy hub. The three major DSOs in the Netherlands are all engaged in pilot projects developing energy hubs. Liander initiated the first Dutch energy hub pilot at the Schiphol Trade Park, testing a virtual grid. While the project is branded as an energy hub it exhibits the closest similarity to a VPP (see Section 1.3), as companies are not physically interconnected and only cooperate on their electricity use. Stedin is involved in a pilot project in Tholen, where experience is gained on collaborative agreements to formulate a contract for a shared grid connection [155]. This project most resembles a microgrid. A few more similar projects can be found at other DSO's.

All energy hubs mentioned here are labelled as 'pilot projects' and are used as learning projects. Organisational structures, legal frameworks and technicalities are currently researched in order to develop the concept. Examples of these developments are the legal frameworks that are currently being developed by the National Grid Congestion Action Plan (LAN in Dutch). Some of the pilot projects are used to experiment with frameworks [75]. Another project that is currently in development is a roadmap for establishing an energy hub [18]. Meant to form a comprehensive set of steps for a cluster to follow in the implementation of an energy hub. These are a few of multiple tools needed to progress the implementation of energy hubs nationwide as solution to grid congestion. With the congestion map of the Netherlands becoming increasingly red it becomes clear that an effective large-scale approach must be adopted [116]. In addition to stimulating entrepreneurial energy prosumers to provide flexibility and developing frameworks, a national top-down approach can help boost the development of pilot projects, as expressed by the Dutch Ministry of Economic Affairs and Climate Policy [109]. Getting insights into what infrastructure, type of organisations or industry might be beneficial in the development of an energy hub can help identify priority regions where energy hubs can optimise the utilisation of energy resources and thereby alleviate grid congestion. Furthermore, applying these insights to identify priority regions in the HIC Rotterdam will provide valuable guidance for the Port of Rotterdam in driving energy hub implementation.

2.2. Knowledge gap

Through an extensive literature search supplemented by conversations with experts from the Port of Rotterdam on infrastructure and energy in the HIC, a gap in academic understanding and practical knowledge on energy hubs has been identified.

After reviewing academic discussion it can be concluded that many studies have contributed to the development of the energy hub concept. Part of these studies incorporate the effect of energy hubs on grid congestion, the subject of interest for this thesis. Nearly all of these studies evaluate the effect on grid stability, thereby adopting the grid operator's perspective. A reversed approach analysing the effect of congestion on the operation of an energy hub is seldomly studied. The amount of literature on energy hub pilots in the Netherlands exemplifies little practical knowledge has yet been gained. The role energy hubs can play in the facilitation of the energy transition is emphasised by both businesses and government discussing energy hub implementation in the Netherlands [109]. Therefore, a preliminary exploration will be performed to find indicators of potential energy hub implementation for industries in the HIC Rotterdam.

For businesses to invest in such an energy hub solution, thereby accelerating the concept's evolution, it is necessary for a strategy to be resilient towards the future. The uncertain character of the energy system makes that a robust strategy needs to proliferate in a wide variety of future scenarios. This is where the academic discussion is particularly lacking. Though studies have explored the performance of many types of energy hubs through various methods there is still little knowledge on the development of robust adaptive strategies for industrial energy systems. While robustness has been examined in a one-dimensional uncertainty analysis in Kasivisvanathan et al. [76], the causality between multiple external factors influencing the energy transition calls for a multi-dimensional scenario set to properly assess robustness. Furthermore, a consumer-oriented approach is rarely adopted in research examining energy hubs in congested systems, despite businesses playing a pivotal role in maintaining a stable grid as highlighted by the Dutch government in the LAN [85]. Mittelviefhaus et al. [111] adopt a consumer-oriented approach on grid congestion for the mobility sector. The rhetoric for the adopted approach inspired this research, though here it will be applied in an industrial context. The study by Mittelviefhaus et al. encompasses multiple decades in the decision-making process for strategic planning purposes, an aspect that will be adopted in this research for the exact same reason. Another example of an adaptive robust model for examining energy systems is described in [3], however only for worst-case optimisation. A project that does include a long-term multi-dimensional scenario set combined with an adaptive modelling method in an industrial context is the Gridmaster project. The knowledge gained from this project will be expanded in this thesis by applying a finer scope in the hope to develop a faster design process while still achieving traceable outcomes. The Gridmaster method is further altered by a different perspective as the method adopts a grid operator's perspective while the industry is the problem owner in this research. To conclude, this research aims to add knowledge on robust decision making under deep uncertainty for the energy system of a carefully selected industrial cluster by simulating a plethora of possible scenarios and analysing what external factors drive certain parameters.

2.2.1. Contribution and research questions

This research can be used for early stages in strategic planning of industrial energy hubs. The research distinguishes itself from previous work by:

- developing a preliminary set of indicators that help identify brownfield locations with high potential for energy hub integration
- adopting a business-oriented approach that aims to make optimal use of the grid capacity still available in a congested area
- designing a robust adaptive model for a brownfield energy hub to account for uncertainty regarding future changes in the energy system and be able to anticipate on these changes
- optimising over a multi-dimensional scenario set in order to capture causal relations between external factors that influence the operation of the energy system

From the identified knowledge gap a main research question emerges:

How can a robust adaptive strategy be developed for an energy hub that enables industrial activities within the congested HIC Rotterdam in a changing energy system?

A set of sub-questions gives structure to the research that aims to answer the main research question:

1. *What are the primary factors contributing to grid congestion in the HIC and how do these factors interact to create grid congestion?*
2. *What types of energy hub are applicable in the HIC Rotterdam?*
3. *What uncertain energy system developments might influence the integration of an industrial cluster into an energy hub within the HIC?*
4. *How can the effects of an energy hub on changing energy use in a congested area be modelled?*
5. *What factors influence the success of the implementation of an energy hub in the HIC in an evolving energy landscape?*

3
Methodology

In the pursuit of answering the research question presented in the previous chapter, a suitable methodology is of great importance. This chapter serves as a roadmap that describes the systematic approach undertaken to answer the sub-questions in subsequent order. Both qualitative and quantitative methods will be adopted to conduct this research. The research flow that illustrates the systematic approach adopted in this research is presented in Section 3.1. Methods to gather data that will help understand the congestion problem faced in the HIC are described in Section 3.2, as well as methods to gather data for further stages in the research. The procedure that guides the search for a representative industrial cluster is described in Section 3.3. The analysis on electricity load profiles of companies that provided data is then described in Section 3.4. The process and outcome of designing scenarios that describe the cluster's evolution pathways over time are presented in Section 3.5. Then, the modelling and simulation approach are discussed in Section 3.6. The method used to evaluate the simulation results and develop a robust adaptive strategy is described in Section 3.7. Lastly, the motivation for the adopted research approach is discussed in Section 3.8. For each research phase limitations on the adopted method are discussed.

3.1. Research flow

A structured overview of the research process flow is presented in Figure 3.1. A logical flow of activities is shown, where the output of one project phase forms input for the next phase. The first four chapters provide an introduction on the subject and describe the adopted approach in this research. Chapters 4 until 9 give answer to the five sub-questions. The main research question is then answered in Chapter 11. Figure 3.1 shows for each research phase the topics that are covered in the thesis, together with the method(s) used for each phase, the phase's output and which sub-question is answered.

3.2. Data gathering methods

During the execution of this research multiple data gathering methods are used. Much of the information presented is gathered from literature sources. These sources are in some cases supplemented by interviews held with experts in the field. After the cluster selection, data needs to be obtained from industry parties. Lastly, a workshop is held to aid in the scenario design for the chosen industrial cluster, which will be modelled later on in this research.

3.2.1. Literature review

From the research process flowchart in Figure 3.1 it becomes clear that reviewing literature is an important method to acquire knowledge for this research. In most chapters literature is reviewed to gather information that helps to answer the sub-questions. For Chapters 1 and 2, the research comprises solely of a literature review. Chapter 1 describes the motivation for this research and provides background knowledge on the subject. The aim of Chapter 2 is to find a gap in the academic literature on energy hubs. In order to find this gap the following sequential steps are followed:

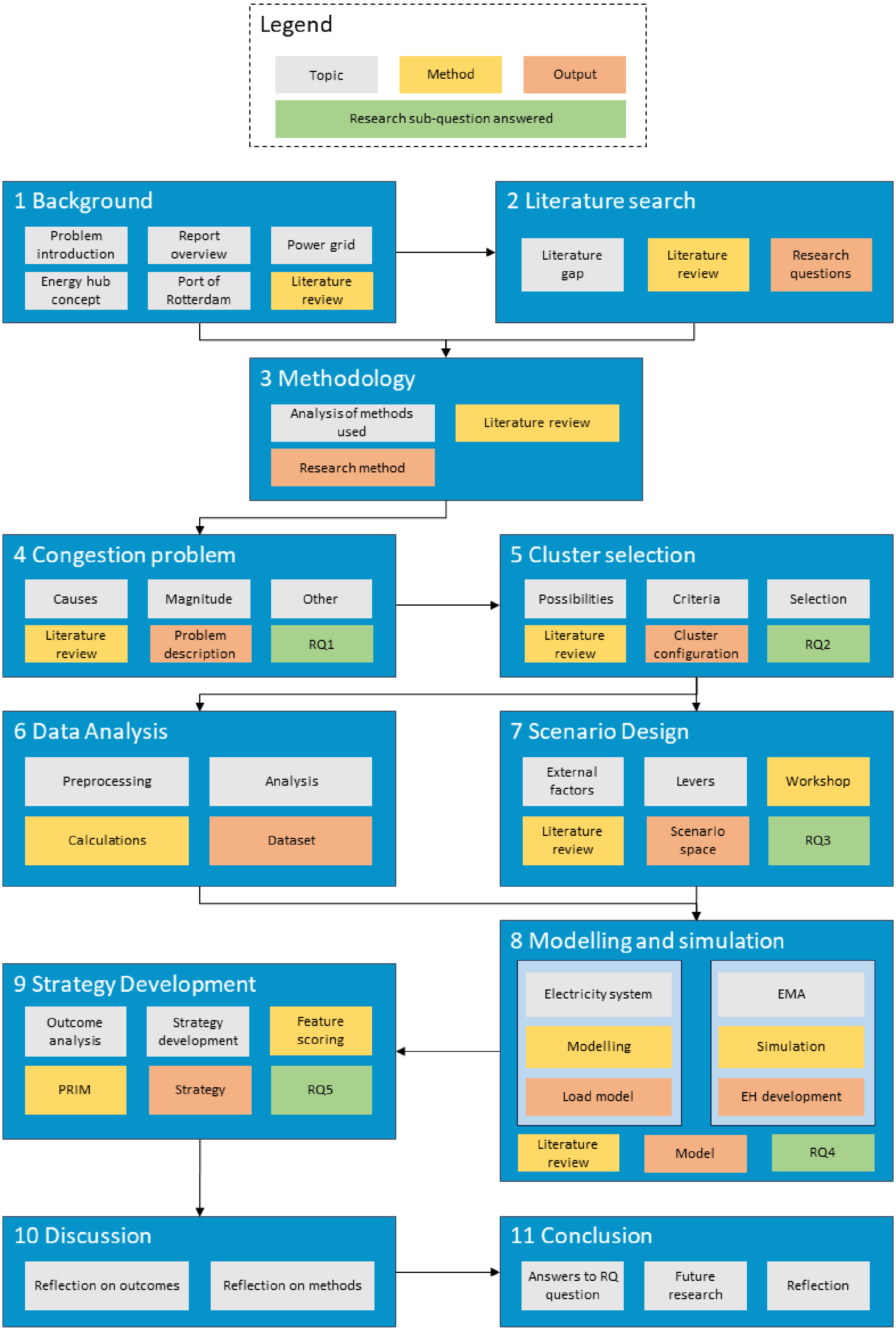


Figure 3.1: Research process flowchart

1. Use key words to find appropriate literature
2. Explore additional literature from references
3. Collect relevant literature
4. Find common topics in literature
5. Decide on topic(s) of interest
6. Gather all relevant literature available on topic(s) of interest
7. Find academic knowledge gap

It should be noted that for step six the search is limited by the availability of articles. The databases accessed for this review were Scopus and Web of Science. For some academic literature in these databases no access could be gained, these are therefore not included in the literature search.

When conducting a literature review by consulting only two databases, there is a potential risk of obtaining an incomplete perspective on the entire academic discourse. To mitigate the limitation of a narrow view, an effort is made to broaden the search by consulting Google Scholar on topics of interest. Since Google Scholar uses a different algorithm compared to Scopus and Web of Science, the review was extended with additional studies in some occasions. Regarding the search string, the risk exists of constructing a string with limited or biased results. To mitigate this risk the search is extended in different stages by snowballing from highly regarded studies. Literature search results for which no access could be gained an effort was made to find a study with similar focus and scope. Lastly, the bias of publication can skew the conclusions drawn from literature reviews. Since the topic is rather new articles that publish positive results will gain more attention compared to negative outcomes, possibly resulting in an opportunistic view of the potential of energy hubs in the energy system of the future. It is therefore of great importance to be critical towards potential possible outcomes of this research and strictly evaluate if studies used for validation operate in similar circumstances. Moreover, a sensitivity analysis will be essential to properly value the results of this research.

3.2.2. Interviews

For the first step of the research, understanding the problem of grid congestion, a study into published reports by TenneT and Stedin will be conducted and databases will be reviewed. From this study, new questions will arise. The goal is to get a complete understanding of the scope of the problem and concrete barriers to overcome. Interviews with experts on the grid in the HIC from both TenneT and Stedin will extend this understanding. In the following chapter, selection criteria are compiled to distinguish industrial clusters with a potential for energy hub integration. A literature study on academic papers and papers from parties experienced in setting up an energy hub will help identify potential synergies to exploit. Nevertheless, while some synergies might be theoretically possible with capabilities present in the HIC, practicalities might prevent certain configurations from materialising. Interviews with experienced parties will help in building a sound list of criteria that will isolate one or multiple configuration(s) for an industrial cluster. Furthermore, in the scenario design part of the research, expert interviews will help guide the creation of the investment paths and scenario space. This will be supplemented by the outcomes of a workshop. Furthermore, modelling expertise on energy hubs might improve the effectiveness of the model and ascertain its applicability to real-life situations. Lastly, consultation with experts can help verify results in the later stages of the research where the model is tested and effects on the industrial cluster are analysed. The interviews conducted in this project are meant to add knowledge where publicly available sources are limited. As the exact answers from interviews will not directly form inputs for this research no transcript of the interviews will be presented in this report.

Limitations of expert interviews might arise from the over representation of certain groups, impacting the objectiveness of the provided input. Especially the view of the port authority might be disproportionately included in the study. Subjectivity might also arise as a result of misinterpretation of statements by the researcher. Additionally, the objectivity of the interviews is already constraint by the subjective construction of interview questions by the researcher. These limitations are mitigated by gathering insights from different stakeholders on the subject by including opinions from grid operators, industry players and the port authority who all have conflicting interests. Biases from the researcher are mitigated by seeking feedback on results and the documentation thereof by supervisors.

3.2.3. Data requests

Following the cluster selection phase data will need to be gathered from cluster types that have been selected. Based on the outcome of this phase certain companies will be approached to ask for their participation in this research. Electricity load profiles in particular are needed as input for the energy system model load parameters. Depending on the outcomes of Chapter 4 a certain scope, resolution and period are required. The broad network of the Port of Rotterdam hopefully helps in finding companies willing to participate. Preferably, multiple datasets can be obtained in order to validate outcomes. The validation can be improved if more industrial electricity load profiles can be found to compare results.

A significant risk for the successful execution of this research is associated with the acquisition of electricity load data from industry parties. As it relies on the willingness of companies to participate, it is first of all beneficial to establish contact with as many companies as soon as possible. Grid operators might also be able to provide the required data. Given that load profiles may contain sensitive information, companies might be hesitant to share such data. To address this sensitivity, various measures can be implemented. These include anonymising the data, modifying it to conceal specific characteristics, or placing the thesis under embargo for a certain period before publishing. If no company is found willing to participate, a public search will need to be done on industrial electricity load profiles. Preferably, from industries with similar characteristics as the industrial cluster selected in Chapter 5. Alternatively, data can be fabricated using assumptions on operation. These assumptions could be based on descriptions of energy use from product specifications or reports on companies' operation.

3.2.4. Workshop

A workshop will be held in the scenario design phase to expand and simultaneously limit the proposed scenario set. Similarly to the cluster selection, ideas inspired by theory will become more robust when validated with practical knowledge. An efficient way to test the proposed ideas will be to set up an afternoon dedicated to discussing the relevant factors influencing the energy hub, input parameters of the model, their concrete values and future pathways that will be interesting to evaluate. The workshop will be structured along these topics. From the data acquisition a number of companies will be chosen to model. Experts on these industries from the Port of Rotterdam will be invited to participate in the workshop as well as operators from the companies if data can be gathered.

Similar limitations are associated with a workshop compared to an interview where subjectivity arises due to the selection of participants and interpretation or preparations by the researcher. The aim of the research will therefore be to invite experts from different stakeholders. Again, the subjectivity of the researcher will be mitigated by seeking feedback from the supervisory committee.

3.3. Cluster selection

With a clear overview of the congestion problem, clusters with high potential to alleviate congestion now need to be selected. The process for selecting configurations for potential energy hubs in the HIC involves several steps:

1. Explore potential energy hub input, output, conversion and storage components
2. Apply exclusion criteria to list of potential components
3. Apply criteria particular to HIC
4. Define potential cluster compositions
5. Establish boundary conditions for energy hub integration
6. Perform a mapping exercise in the HIC
7. Design an energy hub configuration based on obtained load profiles

Initially, an exploration is conducted to identify the potential input, output, conversion and storage components that could make up an energy hub. This involves reviewing academic journals, reports, and articles to gain a comprehensive understanding of potential energy hub components.

Now that a full list of possible components is drafted it will be subjected to a set of exclusion criteria. Refinement of the list involves applying criteria such as Technology Readiness Level (TRL) and capacity. Specifications and additional criteria are derived from the insights presented in Chapter 4, complemented by information gathered through stakeholder interviews.

Next, an investigation into the energy flows within the HIC will be carried out to determine the available inputs, outputs, conversion and storage technologies. An analysis will be performed to match the required inputs for conversion and storage technologies to the available energy inputs and outputs in the HIC. A focus should be placed on the availability of conversion technologies. As the area houses a wide variety of industries with various forms of energy flowing through, it is worth assessing if different energy carriers can be utilised to help meet the increasing electricity demand. It should be mentioned that some of the exclusion criteria in this step might not be as strict as in the previous step as developments in the HIC might result in certain criteria being assessed differently in a few years time.

After the complete list is narrowed down by applying the exclusion criteria different technologies can be combined to make up a number of compositions. A composition describes the set of components that make up the energy hub. Depending on the input or output energy carriers that are required for the respective conversion and storage technologies certain energy hub compositions can be designed.

Before an energy hub can be established certain prerequisites might need to be met. Research into legislation, financial or other boundary conditions will complete the list of actions necessary to start an energy hub.

To find a cluster meeting the necessary requirements a mapping exercise is performed in the industrial cluster, guided by the developed compositions for energy hubs. Sites meeting the specified requirements are approached to gather information on their operation.

Depending on the data that will be obtained a design can be made for the energy hub configuration that will serve as case study for this research project. In this final configuration components can be added that can improve the energy hub's performance.

The goal of this phase is to find a scalable industrial cluster. Since, in order to alleviate grid congestion in the area, and possibly other areas as well, multiple clusters need to provide flexibility to the grid. Two possible approaches can be adopted. Either a single energy hub design is found that represents multiple industrial clusters in the HIC. For this approach a configuration under normal operation is then compared with alternative configurations including varying degrees of energy system integration. This approach allows different types of system integration to be compared. Another approach that can be adopted is when multiple energy hub designs are found that represent different types of industrial clusters present in the HIC. For each configuration a model can be constructed that includes energy system integration. The second approach allows different industrial clusters to be compared in order to gain maximum impact from the energy system integration efforts. Which approach will be pursued depends partly on the outcome of the mapping exercise and partly on the availability of data on industries' operation.

As with the other phases of this research, the chosen process of selecting an industrial cluster to work on for the rest of the research has its downsides. To begin with, the list that will be composed including all possible components that potentially can be implemented in an energy hub will not be exhaustive. Partly, because the search is limited to three databases; Scopus, Web of Science and Google Scholar. Partly, because not all components that theoretically could be included will be discussed extensively in literature already. This does not have to be troublesome as these technologies will often be in the early stages of development. Since the research focuses on solutions that can be implemented immediately, due to the urgent congestion problem, these technologies will most likely not pass the eligibility test. Another risk of applying this method is the researcher's bias that will influence the outcome of the selection process. Support from supervisors will help mitigate this bias and secure that all components which might prove beneficial to the energy hub will be researched.

3.4. Data analysis

Assuming the necessary electricity load profiles will be obtained the next part of the research will be dedicated to a data analysis on the load profiles. This analysis will be performed in Python and will look into the companies' load profile with the aim to gain understanding on the companies' operation. A clear understanding is required to be able to design future scenarios for the cluster in the next research phase.

Furthermore, the data can potentially provide premature conclusions on benefits of pooling electricity connections. Additionally, sizing calculations will be performed for potential energy system solutions. These will be based on optimal ratios for each technology according to literature. The outcome of this chapter will highly depend on the load data that will be obtained.

3.5. Scenario design

After the components are sized, the next step is to design scenarios describing how the various energy systems might behave in the future. The way this is done is derived from the method used in the Gridmaster project [184]. Here an exploratory modelling and analysis approach is applied. The concept of exploratory modelling and analysis is described in 1993 by Bankes [14]. Exploratory modelling allows decision-makers to test hypotheses over a wide range of future scenarios, in contrast to predictive modelling where a target system is used to describe future behaviour. An open source library dedicated to this type of modelling is the Exploratory Modelling Workbench. This workbench makes use of the XLRM framework to structure the modelling problem. This framework is used to group elements of the analysis into four categories, in order to come up with a wide range of future scenarios. External factors 'X' are factors that are outside of the control of decision-makers, nonetheless may prove important drivers for change. For this research external factors will be chosen that directly impact the cluster for the sake of simplicity and interpretability. For example an external factor like the development of the hydrogen economy therefore needs to be broken down to a scope in which the effect on the cluster can directly be estimated. Policy levers 'L' are actions that comprise the investment strategy of the decision-makers. An example can be the installation of an e-boiler. Relationships 'R' describe the way the energy system behaves, in this research the relations 'R' are described according to the energy hub model method by Geidl et al. Finally, metrics 'M' are outcome measures that decision-makers can use to draw their conclusions [90]. This research is interested in the effect of developments in the cluster's operation on its electricity use, especially in relation to the allowed transmission capacities. Therefore, the overload on the cluster's grid connection will be the metric to evaluate the scenarios on.

In the next step, which will be performed after the model has been constructed, each external factor will be quantified. The effect of each external factor is described by a set of parameters which will take on different values depending on the range of projections for the future outlook of the development. To give an example, the completion of a grid expansion project will result in an increased capacity for the grid connection. The size of the scenario set scales exponentially since each scenario corresponding to an external factor can be matched with every scenario of another external factor. In the case ten external factors are drafted, with each 4 different parameter values, the size of the scenario set will amount to 4^{10} = 1 million different scenarios. Drawback of such a large scenario set is the computational effort it requires. To keep the required computational time within reasonable limits different solvers can be tested on their speed. If it seems that all solvers require a significant amount of time to compute outcomes, or require more computational power than is available, sampling might help to generate representative datasets from the complete scenario set. The EMA workbench that will be used for the analysis uses Latin hypercube sampling by default, a method that aims to extract a representative set of scenarios from the complete scenario set [83].

3.6. Energy hub modelling

The next phase of the research intends to model the behaviour of the selected industrial cluster. A simplified explanation of the approach will be provided here. For a more elaborate explanation on the complete modelling procedure can be referred to section 8. The first step towards simulating future cluster scenarios is modelling the cluster's electricity system. A focus on the electricity system is chosen since the research is interested in finding desirable scenarios for the cluster's operation in relation to the electricity transmission capacity, as the area is currently labelled as congestion area. For the next step this model is transformed to a model that is able to match the electricity loads to the capacity of input electricity for every scenario. Finally, an analysis is done on the outcomes of the scenarios. Both models will be built in Python. For the second model the EMA workbench will help in generating scenarios and performing simulations. Also, modules from the EMA workbench can be utilised to perform analyses on the simulation results. A brief description of the modelling and simulation steps is given below. In Chapter 8 the modelling techniques will be discussed in more detail.

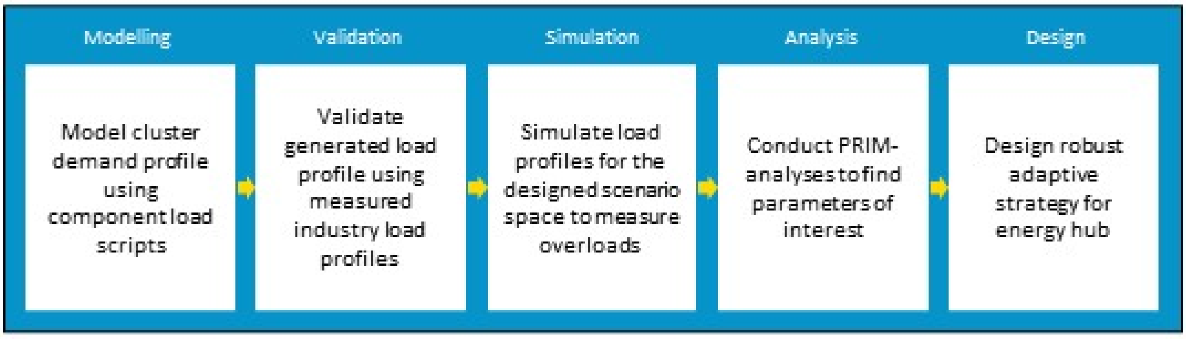


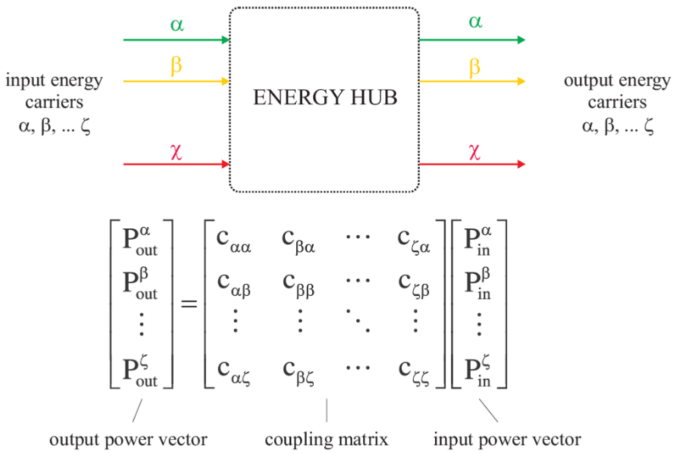
Figure 3.2: Structured overview of modelling approach

3.6.1. Electricity load model

The electricity load model will consist of a concatenation of the loads of the different components in operation at the cluster's companies' sites. Every company in the HIC has a set of components located on its site that together make up the electricity demand. Depending on the type of companies that will be selected in Chapter 5 these components might range from distillation columns to steam turbines, cranes or pumps. The sum of the load of every active component at every timestamp will form the cluster's load profile, calculating this for 35,040 timesteps simulates the cluster's quarterly load profile over a year. Each component's load characteristic can be programmed in a Python script. The electricity load profiles acquired from industry parties will initially be used to draw inspiration from for the design of the cluster's operation. After the construction of the model the industry load profiles can be used to validate the load profiles generated by the electricity models and possibly tune parameters.

3.6.2. Simulation model

The calculation of the load profile of the cluster using the electricity load model can be seen as the calculation of a single scenario. In Chapter 7 the scenario space will be designed. The output of this chapter will be a matrix of scenarios in which a list of factors can be expressed using a list of values. The EMA workbench from J.H. Kwakkel [83] can be applied to input the scenario space into the electricity model. In this electricity system model the load is matched to the electricity input capacity for each scenario, similar to the energy hub modelling method by Geidl et al. In Figure 3.3 this method is visualised, where the output power vector described the loads, the coupling matrix the conversion steps and the input power vector the required input electricity to meet the demand. The overload in every scenario will then be the metric used to evaluate the scenarios.



$$\begin{bmatrix} P_{out}^{\alpha} \\ P_{out}^{\beta} \\ \vdots \\ P_{out}^{\zeta} \end{bmatrix} = \begin{bmatrix} c_{\alpha\alpha} & c_{\beta\alpha} & \cdots & c_{\zeta\alpha} \\ c_{\alpha\beta} & c_{\beta\beta} & \cdots & c_{\zeta\beta} \\ \vdots & \vdots & \ddots & \vdots \\ c_{\alpha\zeta} & c_{\beta\zeta} & \cdots & c_{\zeta\zeta} \end{bmatrix} \begin{bmatrix} P_{in}^{\alpha} \\ P_{in}^{\beta} \\ \vdots \\ P_{in}^{\zeta} \end{bmatrix}$$

Figure 3.3: Method for modelling an energy hub as proposed by Geidl et al. [50]

3.7. Analysis and strategy development

After the electricity system model is run to calculate the overloads in all scenarios the EMA workbench can be utilised to conduct analyses on the results. Similar to the Gridmaster project the Patient Rule Induction Method (PRIM) can be used to find parameters that have a more significant effect on the outcome than others. Drivers for negative outcomes can be identified as well as for positive outcomes. This allows for the design of desirable future pathways. Different future scenarios can also be tested using the EMA workbench and the two models to evaluate what would happen if, for example, certain climate policies would materialise. Combining all this acquired knowledge on future developments of the industrial cluster and its surrounding energy system enables the development of robust adaptive investment strategies for the selected industrial cluster. The depth of the acquired datasets will determine whether strategies can be extended to apply to other industrial clusters in the HIC.

3.8. Motivation for approach and reflection

There are various reasons for adopting this research approach. Traditionally, in the context of modelling future system developments an estimate was made on the 'most-likely' version of the future. The problem with predictive models for the future is that they are based on guesses at future details and mechanisms. The uncertainty surrounding the future state of the energy system makes it impossible to correctly estimate its characteristics. These uncertainties encompass factors such as technological breakthroughs, the dynamic nature of the industry, and the constantly evolving energy policies. Moreover, various stakeholders, including the electricity market and potentially emerging spot markets for hydrogen or methanol, can exert a significant influence on the system's behaviour. Hence, the resulting model cannot be taken as a reliable image of the target system. Exploratory modelling is a method that focuses on exploring the implications of varying assumptions, rather than modelling a 'most-likely' but hardly accurate version of the future [14].

These factors that might influence the development of the industrial cluster are the building blocks of the scenarios. EMA is used to offer computational decision support for Robust Decision Making (RDM) under deep uncertainty. RDM is a set of concepts, processes, and tools that use computation, not to make better predictions, but to yield better decisions under conditions of deep uncertainty. EMA is used to describe how plans perform in a range of plausible futures, and then to identify policy-relevant scenarios and robust adaptive strategies [105, 89]. The evaluation of the system's future performance is the final goal of this research, answering the main research question. In order to get to this final evaluation the process steps as described in Figure 3.2 are followed.

For the project's stakeholders, which include the Port of Rotterdam, industry parties and grid operators the precise numerical values and results may not be of great importance as the method is not designed to find an 'ideal' energy hub configuration. Rather, the benefit lies in identifying future pathways and possibly no-regret investment decisions with the most substantial impact. This model in combination with the scenario set might serve as a tool wherein companies can implement their own system characteristics and beliefs for future scenarios allowing them to investigate the implications of system integration options.

The interpretation of these results should keep in mind the limitations of this modelling approach. The first one being the complexity of it. This research hopes to get traceable outcomes by applying the method on a simple case, a single cluster, as well as decrease complexity in the modelling design. Next to the smaller scope this research differs from the Gridmaster project in the business-oriented approach it adopts. The risk that comes with this approach is that grid congestion might be worsened instead of improved if clusters increase their consumption by creating smart hubs. Due to the complexity of the grid's structure in the HIC it is not possible to evaluate the effects of integrating a cluster on congestion within the scope of this research. An effort will be made however to assess the effect of an energy hub on the cluster's coincidence factor in the data analysis phase. This factor indicates the load on the grid by estimating the aggregated load of the companies in the cluster.

4 Congestion problem in the HIC Rotterdam

This chapter aims to answer the first sub-question by discussing the nature of grid congestion in the HIC Rotterdam and its implications for companies located in the area. The analysis on the current status and factors contributing to the current problem are largely based on the congestion study performed by TenneT that was published on October 18th 2023 [160].

A quantification of the congestion problem in the HIC Rotterdam is presented in 4.1. Following the problem description Section 4.2 discusses the possibility of applying congestion management. Congestion problems that remain after applying congestion management are described in Section 4.3.

4.1. Magnitude of the problem

In 2022, the port emitted 22.5 million tons of CO_2, accounting for 15% of all CO_2 emissions in the Netherlands [55]. The port authority recognises its responsibility in reducing emissions and has set targets in line with the 55% emissions reduction by 2030 of the Fit for 55 package and 0% emissions target in 2050 by the EU. As with other decarbonisation efforts, a crucial part of the energy transition in the HIC Rotterdam is realised by electrification of processes now depending on fossil fuels. 2.5 Mton CO_2 reduction can be achieved by 2030 through electrification alone. Electrification however is hindered by the inability to install new grid connections. TenneT mentions rapid developments in growing electricity demand including industrial electrification, expansion and new business as causes for the congestion [160].

Load flow calculations conducted by TenneT revealed that the 150 kV connections between Maasvlakte-Europoort and Botlek-Geervliet will form significant bottlenecks. These connections are shown in the map on Figure 4.1. These high-voltage power lines, operated by TenneT, are the primary limiting factors in the area. To refer back to the traffic analogy from Subsection 1.2.3, the electricity highways are congested at times. Consequently, all subordinate power levels are affected by the constraints in the high-voltage grid. Therefore, even if Stedin-owned power lines and substations at a lower voltage level have sufficient capacity, transmitting additional power is not possible due to these high-voltage grid constraints. The effect on congestion for the HIC Rotterdam is shown in Figure 4.2.

The load flow calculations indicate a total available transmission capacity of 570 MVA for the area. With the help of power electronics this can equal an active power capacity of 570 MW. Next to the available transmission capacity the congestion research calculated the required and requested transmission capacity. These are elaborated on in the subsections below Figure 4.3. No new requests could be made from the moment congestion was announced in the advance notice in November 2022. At that moment the queue amounted to 426 MW. The results of the congestion report are visualised in Figure 4.3. It is evident that already in 2023 the available transmission capacity falls short of both the required and requested capacities. This deficiency only increases towards 2029.

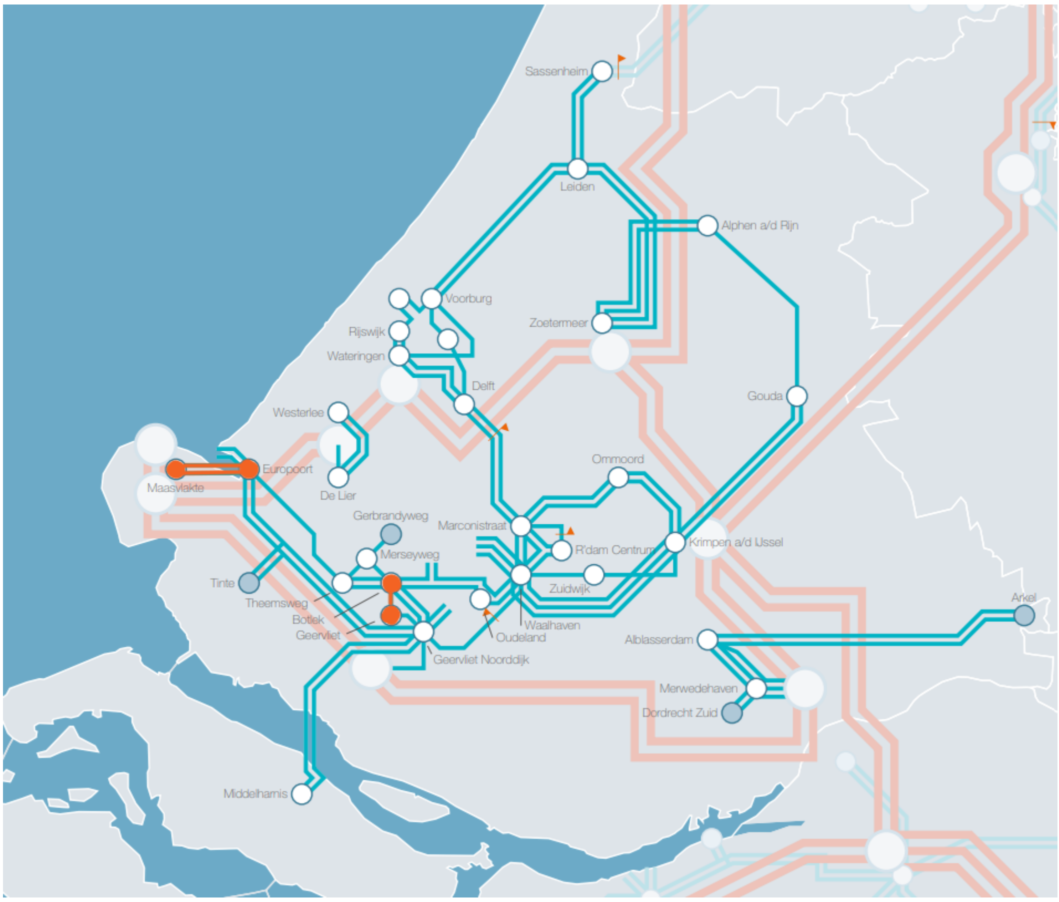


Figure 4.1: 150 kV power lines in South-Holland (per 1-1-2024), bottlenecks are highlighted in orange [125]

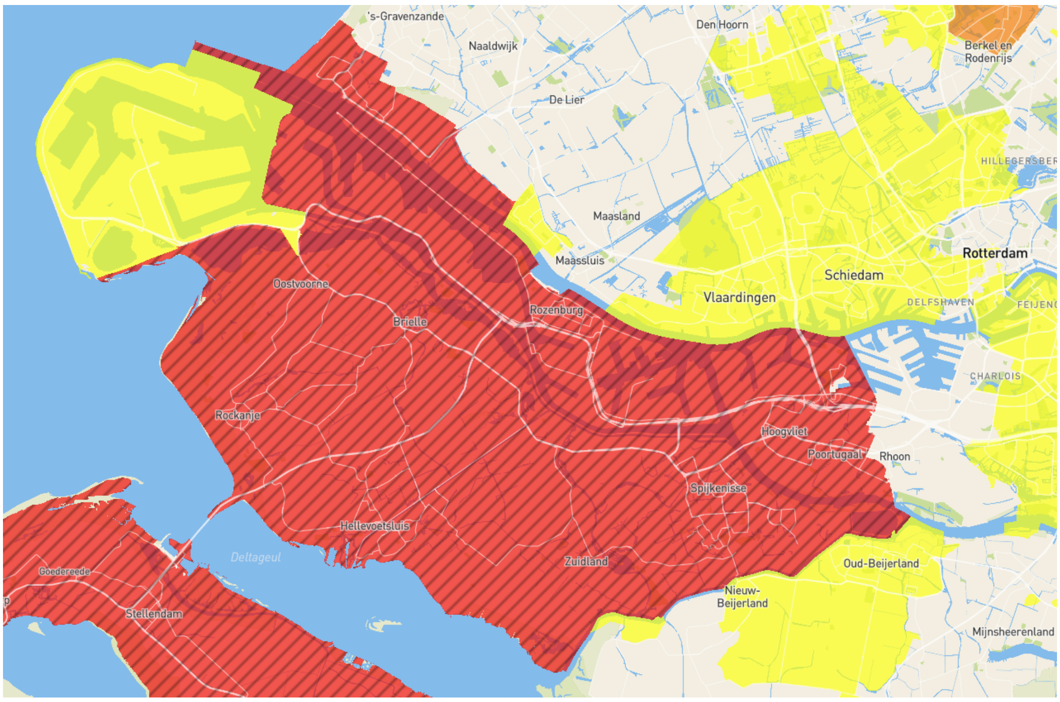


Figure 4.2: Map of congested areas in the HIC Rotterdam, red indicates no capacity, yellow indicates limited capacity [116]

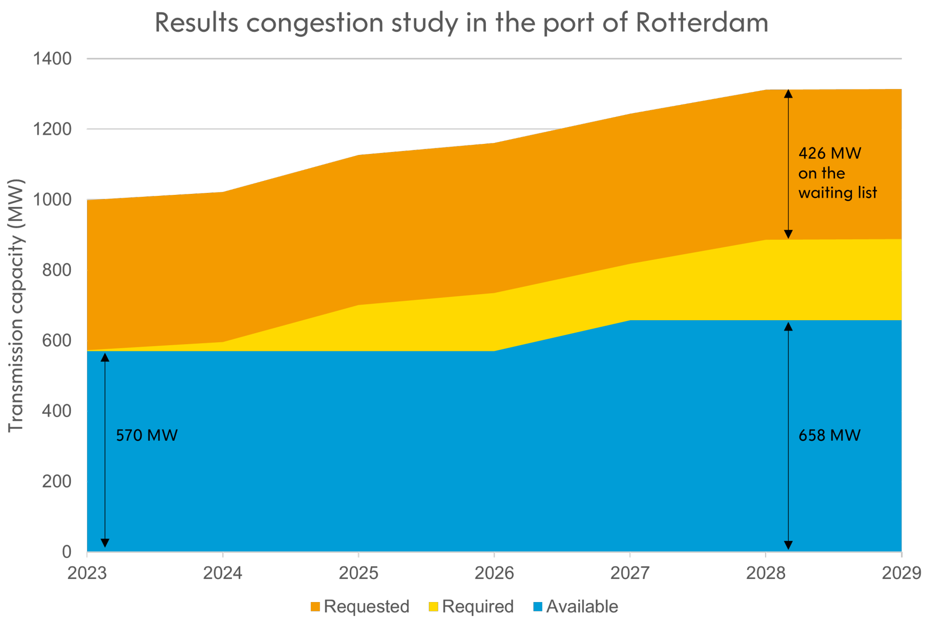


Figure 4.3: Results from the congestion report from TenneT show a lack of transmission capacity in the coming years[1]

How remaining capacity is calculated differs per situation and is therefore not transparent to third parties. This sometimes makes it difficult for connected parties to understand why there is ”suddenly” no transport capacity available somewhere and it is difficult to estimate what possible solutions might be.

4.1.1. Available transmission capacity

As the calculations showed, the current available transmission capacity for demand is 570 MW. Determining this capacity in TenneT’s meshed grid, however, is not straightforward. Although the technical transmission capacity of individual network elements is known, the available transmission capacity is not a simple addition of these values. For instance, the extent of overload is greatly influenced by local generation and consumption, as these influence the direction and intensity of currents in the grid. Additionally, the intermediate voltage grid interconnections between the Oudeland and Vondelingenweg substations and the 150 kV Rotterdam Waalhaven substation contribute to overload issues. The phase shifter[2] at Europoort, which can adjust power, further impacts load flow. This makes it complex to unambiguously determine the available transmission capacity. The transmission capacity was therefore determined by analysing the power flows in this part of the grid based on measurements. A situation is taken into account relevant for the congestion and calculated at a typical load on the grid.

From these measurements the main bottlenecks in the network appeared to be the connections between Maasvlakte-Europoort and Botlek-Geervliet. The available capacity is calculated using the characteristics of the Maasvlakte-Europoort connection. Applying the N-1 criterion to the loadflow calculations resulted in a transmission capacity of 570 MW.

As is shown in Figure 4.3 the transmission capacity increases in 2026. This is the result of a capacity expansion project at substation Europoort150 which relieves the previously constraint connection Maasvlakte-Europoort. The available transmission capacity in the entire port area hereby increases to 658 MW. The congestion study focuses on the congestion problem until 2029 as project ’Loadpocket Simonshaven’ is expected to be commissioned at the latest by 2030. With the realisation of this project the available transmission capacity will increase to 2000 MW. Available transmission capacity will then again be sufficient to meet the future requested transmission capacity.

[1]The commissioning date of the expanded Europoort150 substation is adjusted based on the ’Investeringsplan Net op Land 2022-2031’ published after the congestion study

[2]An explanation on the operation of the phase shifter and how its applied is provided in Section 4.2.2.

4.1.2. Required transmission capacity

The required transmission capacity is composed of three parts. It is the sum of the transmission demand of connected parties, the transmission demand of connections not yet established but already contracted, and the transmission demand as a result of autonomous growth. As with the available transmission capacity this is not a simple addition due to the irregular and unpredictable consumption behaviour of connected customers, and uncertain demand of connections not yet in operation.

Transmission demand of connected parties

Due to the irregular consumption pattern various measurements, calculations and models are used to estimate how much capacity is demanded by the connected parties. Simultaneity of new and existing customer requests is hereby taken into account. The coincidence factor expresses simultaneity and is determined by the grid operator based on measurements. This factor gives an indication of how much the peaks of the parties connecting to the same substation overlap. By multiplying the sum of all connections by the coincidence factor, the grid operator gets a better picture of the actual demanded transport capacity. Parties do have a right to the full capacity, so the grid operator calculates with safety margins and remains in discussion with the parties about their expected energy profile. For instance, if a party has a large connection that it rarely fully utilises, the grid operator will take this into account when determining the demanded connection capacity. For these reasons, the grid operator usually assumes that the total sum of connections at a substation can be larger than the capacity of the substation [42]. The new Gridcode even stipulates that due to simultaneity grid operators may connect 110% of the transmission capacity, and up to 150% if congestion management is applied[3].

Transmission demand of contracts issued

The estimated demand of connections still under construction also inhibits uncertainties. First, there is an uncertainty regarding the construction speed of the connection. Then, the moment at which electricity will be consumed remains uncertain, depending on the pace of construction of the associated facility. Lastly, the demand pattern needs to be predicted. Here simultaneity with both new and connection in operation is accounted for. With the contracts signed before November 2022 estimates are made to be able to construct the timelines depicting capacity demand, which are presented in Figure 4.3. Sudden spikes result from the projected connection of issued contracts.

Autonomous growth

Lastly, the autonomous growth of all connections combined is estimated and added to calculate the required transmission capacity. Each customer has a certain Contracted Transmission Capacity (GTV in Dutch) that it is allowed to use. Typically, when a party requests a connection it would do so with future growth in mind. This practice stems from the historical availability of ample grid capacity at a relatively low cost. Parties would secure electric capacity, allowing for potential expansion if they had such plans. In Figure 4.3 a steady rise in required transmission capacity is included because of autonomous growth. It is not specified what the individual contributions are of the three types of demand. Altogether, a required transmission capacity of 888 MW is estimated for 2029.

4.1.3. Requested transmission capacity

The requested transmission capacity consists of the required transmission capacity supplemented by the waiting list for connection to the grid by customers of either TenneT or Stedin. All requests that were made after November 2022 were placed on a waiting list. The Contracted Transmission Capacity on the waiting list as of September 2023 was used for the calculation of the requested transmission capacity. At this moment the waiting list added up to 426 MW of transmission capacity. Adding this to the required transmission capacity results in 1314 MW requested transmission capacity.

4.2. Congestion management

The Gridcode Electricity describes the conditions relating to how grid operators and customers should act with regard to the operation of grids, the provision of a connection to the grid and the performance of the transmission of electricity over the grid [118]. In case a new request exceeds the available transmission capacity the grid operator is obliged with the responsibility to find a solution. Grid operators can then resort to mitigation efforts as described in Section 1.2.4. In case these solutions are not

[3] See Section 4.2 for an elaboration on congestion management

sufficient to meet the required connection capacity or do not fit the proposed timeline of the connection, congestion is issued in the area. Article 9.10(1) describes that for an area for which the grid operator has issued an advance notice, the grid operator shall investigate the possibilities of applying congestion management.

The research into the possibility for congestion management is composed of three analyses. A market consultation identifying the flexibility available for congestion management. With the available flexibility known, analyses are conducted on the technical and financial limit as the grid code obliges grid operators to apply congestion management up until these limits. An elaboration on the available flexibility and the applicable limits for the case of the HIC Rotterdam is provided in this section.

4.2.1. Market consultation

Through a consultation with industry players an inventory is made on the amount of flexibility available for congestion management. This was done through two parallel paths. Companies were attended on the role they could play in the mitigation of congestion, after which they could register their available flexibility. Additionally, grid operators TenneT and Stedin conducted interviews with about a dozen companies they believed to be able to make a significant contribution.

TenneT analysed that 322 connections in the area are greater than 1 MW. Via the consultation process responses from 23 of these were gathered. The analysis and consultation show that relatively few customers can provide flexibility, resulting in a limited amount of controllable power available. Reason for this is that most industrial processes are optimised to produce full-time. Generally, the only processes that can theoretically increase their electricity production are CHP-systems of which half operate at maximum capacity already [21]. Only few companies can reduce their electricity consumption but in those cases only slightly. Substantially reducing demand would require a total shutdown of production processes, which comes with high costs.

Determining the amount of available controllable power involves an analysis of the capacity made available at the substation when congestion management contracts are initiated with customers or Congestion Service Providers. The total potential controllable power is determined at 185 MW. However, it is crucial to note that this figure represents the offered capacity by companies and does not accurately reflect the controllable power available for deployment. The discrepancy arises primarily due to a significant portion of controllable power originating from a single customer at a specific location. Generally, flexibility can only resolve congestion if it can be employed in the same grid zone. While this controllable power has the capacity to alleviate bottlenecks in one area, it may worsen bottlenecks elsewhere if not applied carefully. The grid zones of the HIC Rotterdam are meshed based on their voltage level. A detailed overview of the grid zones for the 150 kV level, where bottlenecks develop, are shown in Appendix B. Furthermore, flexible capacity can only be employed if it is available at times of peak demand. Consequently, the defined threshold for available controllable power, which can be deployed without adverse effects, is set at 35 MW.

The available transmission capacity in the congestion period needs to be split into two phases, before and after the commissioning of the Europoort150 substation in 2025. Prior to the commissioning, the available transmission capacity stands at 570 MW, while post-commissioning, it increases to 658 MW, as previously indicated. Incorporating the identified controllable power of 35 MW increases the technical limits from 110% to 116% and 115% of the available transmission capacity for the periods before and after 2025, respectively.

4.2.2. Technical limit

Congestion can originate from either limitations posed by transformers or power lines. For the HIC Rotterdam, power lines are the limiting factor, specifically the 150 kV connections. As mentioned earlier, the grid operator is obliged to apply congestion management up until the technical or financial limit. The technical limit is specified at 110% of the available transmission capacity added by the controllable power for the area. The grid can be over-dimensioned due to assumptions on simultaneity, [42]. The technical limit for the HIC is 116% and 115% before and after 2025 respectively, as mentioned in the previous paragraph. The first step of the technical analysis however is verifying if the maximum technical limit of 150% is not breached. If the limit is surpassed the grid operator is no longer obliged to apply congestion management to facilitate transmission capacity [118].

Power system analysis calculations show an overload on the Botlek-Geervliet connection of 171%. Optimising the phase shifter present in the port grid reduces the overload beneath 150%. The technical upper bound of 150% is therefore not a limitation in this part of the grid. The remaining overload needs to be further reduced below the technical limit. This can be done by utilising the controllable power or other technical measures. The available controllable power is determined only at 35 MW, which is insufficient to reduce the overload below 115/116%. Technical measures should therefore be employed.

In academic literature multiple forms of technical measures for congestion management can be found, some of which are discussed in Appendix A. Methods for congestion alleviation are often divided in market-based and non-market based measures. The latter often comprises of technical measures. Some of these might already be applied by the grid operators for regular operations. For congestion alleviation in the HIC Rotterdam there are three technical measures available; employing a capacitor bank in the Botlek region, a phase shifter in the Europoort-Theemsweg connection or grid reconfiguration [160]. An explanation on the functioning of these measures can be found in Appendix A.

4.2.3. Financial compensation

If requested transmission capacity exceeds available transmission capacity, connecting additional capacity leads to congestion. This can be expressed as an annual volume of congestion (in MWh) when connecting a certain amount of additional capacity (in MW). As part of the financial analysis, an estimate is made of the costs of implementing congestion management (€/MWh). This can then be used to calculate the expected costs of connecting a certain amount of additional capacity. The analysis then calculates how much power transmission capacity can be added until the financial limit is exceeded. This constitutes an upper limit to the power to be added by applying congestion management.

The financial limit is €1.02 per MWh of the amount of electricity that can be transmitted with the available transmission capacity in the congestion area during the period for which the congestion has been issued. The available transmission capacity was set at 570 MW until 2025 and 658 MW after 2026. The available transmission capacity is thus multiplied by the number of hours per year (8760) and the financial limit set in the Grid Code. Annual financial limits of €5.1 million and €5.9 million for 2023-2025 and 2026-2029 are calculated respectively. Cumulatively, the financial limit adds up to €38.8 million.

To determine how much congestion management can be applied based on the financial limit, it is necessary to estimate the expected costs of implementing congestion management. This estimate is based on the expected congestion volume, the expected cost per unit of control volume and factors for the efficiency of procurement and redispatch. The cost estimate depends on assumptions based on analyses of redispatch applied in the past. An overview of the estimated utilisation of the congestion budget is presented in Table 4.1.

Table 4.1: Overview utilisation congestion budget

Year	’23	’24	’25	’26	’27	’28	’29
Estimated cost per year (in mln €)	0,0	0,1	5,6	1,2	9,7	25,5	23,4
Cumulative costs (in mln €)	0,0	0,1	5,6	6,8	16,5	42,0	65,4
Utilisation of congestion budget	0%	0%	14%	18%	42%	108%	169%

Table 4.1 shows facilitating the total transmission capacity required through congestion management may exceed the financial limit if the Loadpocket Simonshaven project is commissioned after Q3-2028. However, a shorter congestion period also leads to a lower financial limit. If more flexibility becomes available, it should be examined whether the expected costs would fit within the financial limit, taking the current project planning into account.

4.3. Remaining problem and reflection

Based on the performed analyses by TenneT and Stedin the required transmission capacity including connections currently in construction or already issued and the autonomous growth of smaller consumers can be facilitated when congestion management is applied.

Calculations on the effect of employing technical measures show that overload is reduced on the connections Botlek-Geervliet and Maasvlakte-Europoort from 171% to below the 150% limit. When in addition controllable power is employed, overload is further reduced so that the grid can safely be operated for the required transmission capacity. However, the overload is not reduced below the 110% limit, leaving no possibility for connection requests on the waiting list to be issued. Connection requests accumulating to 426 MW will therefore remain on the waiting list until further flexibility or alternative solutions are found in the HIC. For the congestion management necessary to facilitate the required transmission capacity the financial limit should be closely monitored. The financial limit currently in force may be exceeded in Q3 of 2028. In case new flexibility options or alternative solutions are found the technical and financial limits should be reevaluated in order to verify the possibility of implementing them.

Without the adoption of new solutions, companies on the waiting list will have to wait on the completion of the project 'Loadpocket Simonshaven'. This reality is disastrous for both the business climate as well as sustainability ambitions in the HIC Rotterdam. The HIC Rotterdam contributes substantially to the Dutch economy. However, the business climate will deteriorate in the coming years if grid congestion persists. This not only hampers electrification plans of existing companies but also poses a hurdle to expansion initiatives. Additionally, prospective businesses aiming to establish themselves in HIC Rotterdam will face setbacks as the unavailability of new grid connections impedes the realisation of their business plans. Victor van der Chijs, President of the HIC's business association Deltalinqs, warns for a delay in the energy transition due to grid congestion. Consequently, he foresees that the climate targets for 2030 will be impossible to meet when businesses are not able to electrify. To prevent such consequences he urges grid operators and the government to take drastic measures. Furthermore, businesses can contribute by providing flex capacity and create energy hubs [27].

On the grid operator's side steps can be taken towards finding promising solutions to combat grid congestion. The congestion study indicates the grid in the HIC Rotterdam will reach its limits in the upcoming years. What remains uncertain however is the specific locations and timing of these peak loads. This is however a crucial part in applying congestion management. It is the responsibility of grid operators to describe clearly when congestion will be reached, at what times and for how long, according to the ACM [60]. The complexity of the power grid's structure in the HIC Rotterdam, coupled with the unpredictable behaviour of customers makes it difficult for grid operators to gain useful insights. As an example, for the built environment the electricity demand profile typically shows peaks before and after a regular workday. For the industry such generalisations can not be made since every site has its own characteristics, which are often influenced by market forces rather than the conventional working hours. Furthermore, confidentiality surrounding the intended use of connection requests and investment strategies by the industry also hamper grid operators to make sound predictions on the state of the electricity grid in the HIC. Clear is that limits will be reached sooner than expansion projects will be finished, the exact modelling outcomes presented in the congestion study should however be interpreted as a call for action rather than accurate predictions on the future state of the electricity grid.

Another unknown is the exact execution of congestion management. The application of congestion management at the scale in which it is currently required is new to all users of the electricity grid. This high demand leads to new forms of congestion management to be developed that will allow for a more tailored approach based on companies' operation. Contracts for a group transmission agreement ('Groeps-TO' in Dutch) and collective capacity limiting contract ('C-CBC' in Dutch) are under development at the time this research is conducted. Other forms of alternative transmission agreements are being developed as well. This means that companies that might be able to provide flex capacity are not yet able to complete all contractual agreements as of now. When these agreements are published over the course of 2024 a surge in companies providing flex capacity might unfold.

On the industry side, the unavailability of useful insights from the grid operator's perspective makes it hard to propose solutions to the HIC's congestion problem. While the congested power grid creates problems for the industry it is not its primary concern. The problems that are experienced by the industry in the HIC Rotterdam is not the overload of power cables, rather the limits on electricity supply arising from the overloads. Since companies have multiple reasons to electrify their operation, as established in Section 1.2, it becomes increasingly valuable to look for solutions that open up capacity within the limits of the congested grid in the HIC Rotterdam. Though these solutions will not reduce overloads on the power cables, they will help companies to execute their expansion or electrification plans. As the research question describes, the latter is the problem that is focused on in this research. A business-perspective is thus adopted in the pursuit of solutions for capacity within a congested electricity grid.

5

Potential for energy hubs in the HIC Rotterdam

This chapter outlines the process leading to the ultimate selection of an industrial cluster. Following the outcomes of this chapter, companies can be approached that fit the cluster characteristics in order to obtain data which will guide the conduct of the subsequent research phases. As the methodology describes in Chapter 3, the cluster selection procedure follows a few steps.

Initially, energy carriers are evaluated on their applicability in an energy hub in Section 5.1, along with the corresponding technologies for conversion or storage. The set of all inputs, outputs, conversion and storage technologies forms the basis for the selection process. This set is exposed to exclusion criteria in Section 5.2. Additionally, available energy carriers for the area of interest are researched. Technologies not conforming to these energy carriers are excluded. In the next Section, 5.3, the remaining technologies are compared and a discussion on potential compositions is provided. This is based on both academic literature and interviews with industrial parties in order to validate and enhance the derived conclusions. Next, a mapping exercise is executed in the HIC Rotterdam area to identify locations where energy hubs could possibly be established. This is outlined in Section 5.4. These locations are contacted in order to obtain data on their electricity consumption pattern. Based on the outcome of the mapping exercise and the available load profiles, configurations are constructed. These configurations, that are described in Section 5.5, will form the foundation for the subsequent chapters.

5.1. Possible energy hub technologies

To eventually select an industrial cluster to model, first all possible building blocks are explored. As explained in Section 1.3 there are four distinctive features in an energy hub: production, conversion, storage and consumption utilities. According to the methodology described in the Section 3.3 the first step of the selection procedure is to explore energy carriers, conversion, and storage technologies that can possibly be used. An overview of the possible building blocks per feature is shown below. A complete overview of all components found to be eligible in energy hub integration are listed in Appendix C. This complete selection is narrowed by grouping technologies that show many similarities.

5.1.1. Energy input

Traditionally, fossil fuels have fueled our society. With depleting sources and increasing concerns for the effects of greenhouse gas emissions other forms of energy have seen an increase in their utilisation. For example, biomass-based fuels and renewables are increasingly used to meet our energy demand. An overview of energy inputs described in literature is given in Table 5.1. Some of the listed energy inputs might seem redundant, for example, electricity and solar PV as this generates electricity as well. They do however bring specific requirements and characteristics in the context of energy hub design, which is why they are listed separately. The term 'electricity' refers in this case to the electricity grid, which is able to supply a constant amount of electricity contrary to renewable energy sources.

Table 5.1: Energy hub inputs according to literature and their use

Energy input	Currently used by
Electricity	All industries
Hydrogen	All industries
Steam	All industries
Heat	All industries
Cooling	Refineries, chemical, biofuels industry
Flue gas	Refineries, chemical, biofuels industry
Syngas	Refineries, chemical, biofuels industry
Crude oil	Refineries
Biogas	Biofuels industry
Methanol	Chemical, biofuels industry
Biomass	Power utilities, chemical, biofuels industry
Natural gas	Power utilities, chemical industry
Coal	Power utilities
Wind	Power utilities
Solar PV	Power utilities
Nuclear	Power utilities
Hydro	Power utilities
Geothermal	Power utilities
Solar thermal collector	Power utilities

5.1.2. Energy output

Similar to the previous paragraph on energy input the energy output carriers see a change in utilisation over the last few decades. Table 5.2 displays a list of these produced energy carriers. Again, some listed outputs might seem redundant, such as natural gas and biogas. However, since the necessary inputs and production processes are different they are listed separately.

Table 5.2: Energy hub outputs according to literature and their use

Energy output	Industrial user example
Natural gas	All industries
Steam	All industries
Heat	All industries
Flue gas	Refineries, chemical, biofuels industry
Syngas	Refineries, chemical, biofuels industry
Hydrogen	Refineries, chemical, biofuels industry
Water	Refineries, chemical, biofuels industry
Cooling	Power utilities
Electricity	Power utilities
Biogas	Waste management
Methanol	Chemical industry
Oxygen	Chemical industry

5.1.3. Energy conversion

The next step in the exploration of energy hub components is a review on conversion technologies; a crucial building block of an energy hub as it provides the energy hub its flexibility to employ different energy in- or outputs. Specific conversion technologies are categorised in types based on their operational characteristics. The contents of Table 5.3 are gathered from academic literature and industry documents.

Table 5.3: Conversion technologies used in energy hubs and their estimated capacity in the HIC Rotterdam

Type	Conversion technology	Input	Output
Rotary engines	Steam turbine	FF, B, SG, RH	E, H
	Gas turbine	FF, H_2	E, H
	ICE [b]	FF, BF, SG	E, H
Fuelled heating	Boiler	FF, B, H_2	S[a]
Biogas production	Pyrolysis	B	BF
	Anaerobic digestion	B	BF
Mechanical	Piezoelectric generator	ME	E
Fuel cell (FC)	Solid oxide FC	H_2, O_2	E, H_2O
	PEM FC [c]	H_2, O_2	E, H_2O
	Alkaline FC	H_2, O_2	E, H_2O
	Molten carbonate FC	H_2, O_2	E, H_2O
	Posphoric acid FC	H_2, O_2	E, H_2O
H_2 production	Electric Haber-Bosch	H_2, E	NH_3
	Alkaline electrolyser	E	H_2
	PEM electrolyser [c]	E	H_2
	Gasification	FF, B	SG
	TWSC [d]	H, H_2O	H_2, O_2
	SMR [e]	FF, H_2O	SG
Power-to-heat	Electrode boiler	E	H
	Electric boiler	E	H
	Heat pump	E	H
Heat-to-power	Low-heat ORC[f]	H	E
	High-heat ORC[f]	H	E
	RTG[g]	H	E

B = Biomass, BF = Biofuel, E = Electricity, FF = Fossil fuel, H = Heat, H_2 = Hydrogen, H_2O = Water, ME = Mechanical energy, O_2 = Oxygen, RH = Residual heat, S = Steam, SG = Synthesis gas
[a] Steam generation for a boiler is similar to heat generation, the only difference being that heated water vapour is emitted instead of air
[b] ICE = Internal Combustion Engine
[c] PEM = Proton Exchange Membrane
[d] TWSC = Thermochemical Water Splitting Cycle
[e] SMR = Steam Methane Reforming
[f] ORC = Organic Rankine Cycle
[g] RTG = Radioisotope Thermoelectric Generator

5.1.4. Energy storage

After conversion technologies, storage technologies are now explored. The storage component forms an integral part of an energy hub as it provides flexibility over time. If power supply is insecure a storage component allows a system to continue operating continuously. In combination with energy generation it can even create self-sufficiency. Table 5.4 shows a list of energy hub storage technologies mentioned in literature, categorised on storage principles. [121]

Types describe the scientific principle that allows the energy to be stored. Latent heat is energy released or absorbed by a material during a phase transition, while maintaining the same temperature. Sensible heat is energy that is added or extracted from a source which causes it to change temperature. Thermochemical heat works through a chemical reaction that absorbs or releases heat as opposed to chemical energy storage which is simply storage of a chemical. In electrochemical energy storage electrons are absorbed or released as the result of a chemical process. For electric energy storage electrons are stored through capacitance. Electromechanical is a form energy storage where electricity is used to generate motion or displacement, which can be reversed at a later time. Finally, electromagnetic energy storage describes technologies that create an electric or magnetic field using electricity.

Table 5.4: Storage technologies used in energy hubs and their estimated capacity in the HIC Rotterdam

Type	Storage technology	In-/output	Storage medium
Latent heat	Ice storage	C	H_2O
	Cryogenic air	H	A
Sensible heat	Molten salt	H	S
	Hot water	H	H_2O
	Rock cavern	H	Rocks
Thermochemical heat	Adsorption	H	Sorbent
	Salt hydrate	H	Salt
Chemical	H_2-tank	H_2	H_2
	Salt cavern	H_2	H_2
	NH_3-tank	H_2	NH_3
Electrochemical	Electric vehicle	E	Ch
	Li-ion battery	E	Ch
	Redox-flow battery	E	Ch
Electrical	Supercapacitor	E	EC
Electromechanical	Flywheel	E	ME
	Pumped hydro	E	ME
	CAES[a]	E	ME
Electromagnetic	SMES[b]	E	EF, MF

A = Air, C = Cooling, Ch = Chemical, E = Electricity, EC = Electric capacity, EF = Electric field, H = Heat, H_2 = Hydrogen, H_2O = Water, ME = Mechanical energy, MF = Magnetic field, NH_3 = Ammonia

[a] CAES = Compressed air energy storage

[b] SMES = Superconducting magnetic energy storage

5.2. Exclusion criteria

First energy in- and outputs are tested on their availability within the HIC and their applicability in an energy hub. Then, the lists of potential conversion and storage components are filtered based on a set of exclusion criteria. The used criteria are compiled in collaboration with the Port of Rotterdam. The exclusion criteria are presented in Table 5.5 below, where 'Y/N' is a pass or fail criterion. Efficiency does not have a strict exclusion limit, but is regarded as a soft criterion. An explanation for the use of every criterion is provided below. The conversion and storage components are tested on the criteria after which some are excluded. The excluded technologies are listed at the end of every criterion's description.

Table 5.5: Exclusion criteria

Criteria	Limit
Electricity input	Y/N
Electricity output	Y/N
TRL	> 8
Capacity	> 1 MW
Applicability in HIC	Y/N
Efficiency	

Electricity input

The first exclusion criterion is based on the analysis done in Chapter 4. Here, the problem of limited grid capacity is described, concluding that no additional grid connections can be built before 2030[1]. Therefore, the inclusion of new components in the energy hub that require electricity as energy input is restricted.

[1] No additional connections can be installed before the commissioning of project 'Loadpocket Simonshaven', which is projected to happen in 2030

Electricity output
In the context of an energy hub all energy carriers could possibly be integrated to improve flexibility. The question for this research is which energy carriers and corresponding conversion and storage technologies can be combined to form an energy hub that helps alleviate grid congestion. The aim therefore is to create flexibility so that demand of electricity from the grid connection can be reduced. For companies with a single electricity input, the electricity grid, it becomes necessary to realise an additional electricity input. From this reasoning, it follows that to give answer to the research question, conversion technologies should be included that realise an additional electricity input to a company.

TRL
For the energy hub that is designed it is vital for a technology to be matured so that it can be applied on an industrial scale. A method for estimating the maturity of a technology is its Technology Readiness Level (TRL). The method was developed by NASA in the 1970s for their space technology planning. It is a scale ranging from 1 to 9 where a TRL of 1 indicates results of beginning scientific research are being translated into future research and development, TRL 9 is reached when a technology is 'flight-proven' [104]. The method was originally developed for space technology but is now commonly used to indicate the maturity of other types of technologies as well, even being adopted by the Netherlands Enterprise Agency as innovation policy tool [158]. As mentioned in Section 3.3 the aim of the project is to find a solution that is scalable so that it can be applied to multiple industrial clusters, which would be indicated by a TRL of 9. Nevertheless, given the ambiguity in determining the Technology Readiness Level (TRL) for technologies beyond the scope of space applications and the uncertainty regarding the pace of technological advancements in the near future, a minimum TRL of 8 is considered. The Technology Readiness Levels of all selected components can be found in Appendix C.

Capacity
Each technology can be designed for a range of capacities. Depending on the characteristics of a technology it is suitable for smaller or larger power applications. Since industrial plants operate at power levels of multiple MWs a minimum conversion and storage power capacity of 1 MW is assumed. Capacities less than 1 MW are assumed to be insufficient to support an industry's operation. For conversion and storage technologies the available power capacity is presented in Appendix C.

Applicability in HIC
There might be technologies that have great potential for energy hub integration and meet the other criteria, but are not applicable in the HIC Rotterdam. Reasons for this could be the unavailability of necessary resources or energy flows that are utilised by the technology.

Efficiency
As mentioned in Section 1.2 one of the key steps of the energy transition is energy efficiency. If less energy is needed for final consumption, less energy needs to be produced. In the case of fossil generation this results in less emissions, in all cases it leads to lower costs. Hence, energy efficiency is a crucial part in the energy transition. As the efficiency of a technology might depend on many factors, some of which might not be related to the technology itself, this criterion will only be used to exclude technologies in the case alternatives exist that are clearly more efficient.

5.2.1. Inputs and outputs

The features input and output are the first features that are examined for the HIC Rotterdam. The lists presented before are expanded with their availability in the HIC. For each energy input it is specified whether or not it is currently present at industrial scale in the HIC Rotterdam. In lightgray a preliminary list of carriers is shown which are present as waste streams in the HIC Rotterdam. In a later step these will be used to filter energy hub technologies. Information on industries' operation in the HIC Rotterdam is gathered from the Manufacturing Industry Decarbonisation Data Exchange Network (MIDDEN) studies by TNO and PBL [35, 123, 29, 77, 187, 28, 163, 143, 145, 81, 59, 5, 19, 2].

Table 5.6 shows inputs that can be used to fuel an energy hub. Four of these are not present in the HIC, due to various reasons; apart from the fact that all are capital intensive they also need a favourable location. Nuclear energy needs to be located in a remote area due to safety hazards. Hydropower is generated by water moving with great force, arranged by either height differences or a high flow rate. Both of which are not present in the HIC Rotterdam. A study conducted to explore the potential

Table 5.6: Energy carriers used as input for energy hubs and their availability in the HIC Rotterdam

Energy input	Currently used by	Consumed in HIC
Coal	Power utilities	✓
Crude oil	Refineries	✓
Natural gas	Power utilities, chemical industry	✓
Flue gas	Refineries, chemical, biofuels industry	✓
Syngas	Refineries, chemical, biofuels industry	✓
Steam	All industries	✓
Heat	All industries	✓
Cooling	Refineries, chemical, biofuels industry	✓
Biomass	Power utilities, chemical, biofuels industry	✓
Biogas	Biofuels industry	✓
Methanol	Chemical, biofuels industry	✓
Electricity	All industries	✓
Hydrogen	All industries	✓
Wind	Power utilities	✓
Solar PV	Power utilities	✓
Nuclear	Power utilities	
Hydro	Power utilities	
Geothermal	Power utilities	
Solar thermal	Power utilities	

of geothermal energy in South-Holland reveals promising prospects [87]. However, like hydropower, geothermal energy cannot be harnessed everywhere within the HIC. This is however a prerequisite in the design of a scalable energy hub. Even if it were feasible, the construction of a geothermal generation site poses a significant financial hurdle. While such sites can yield substantial energy output (e.g., 15 MW for the Maasvlakte site), surpassing the typical energy demand of an industrial cluster, the high initial investment makes it economically unattractive. Additionally, high risks are associated with the construction of a geothermal generation plant, as the amount of available energy can only be determined after drilling (personal communication, 2023). Given the high costs and uncertain outcomes, geothermal energy does not fit seamlessly into a scalable energy hub solution. Lastly, solar thermal energy generation is the reflection of direct sunlight onto a fluid that subsequently stores energy by heating up. If sunlight is scattered by clouds it can no longer be focused and is therefore useless for solar thermal energy generation. Due to the relatively high amount of cloudy days in the Netherlands, it is deemed an unattractive area for solar thermal energy generation.

Excluded inputs: Nuclear, hydro, geothermal, solar thermal

From the energy inputs that are present in the HIC there is one that might not be suitable for inclusion in an energy hub. Wind turbines in the HIC Rotterdam have minimum distance requirements in relation to storage tanks. This is because storage tanks that may contain substances of very high concern (SVHC), such as ammonia, can not risk damage from possible breakdown of the wind turbine. This prevents most of the industrial sites from installing wind turbines. Not all sites however are prohibited for wind turbines, as multiple turbines are installed at the Slufterdam at the Maasvlakte and the headland Rozenburg. Whether or not wind turbines can be part of the energy hub configuration that will be modelled will depend on the outcome of the mapping exercise.

Excluded: (wind)

The outputs of an energy hub as described by literature are listed in Table 5.7. For an internationally operating port like Rotterdam, most energy carriers that are consumed are also produced in the port area. Since the port area provides a broad market due to its size and variety of industrial activities, as displayed in Figure 1.2, all energy carriers that an energy hub might produce according to literature, are produced here as well.

Excluded outputs: -

Table 5.7: Energy carriers produced as output for energy hubs and their availability in the HIC Rotterdam

Energy output	**Industrial user example**	Availability HIC
Natural gas	All industries	✓
Steam	All industries	✓
Heat	All industries	✓
Flue gas	Refineries, chemical, biofuels industry	✓
Syngas	Refineries, chemical, biofuels industry	✓
Hydrogen	Refineries, chemical, biofuels industry	✓
Water	Refineries, chemical, biofuels industry	✓
Cooling	Power utilities	✓
Electricity	Power utilities, waste management	✓
Biogas	Waste management	✓
Methanol	Chemical industry	✓
Oxygen	Chemical industry	✓

5.2.2. Conversion technologies

Most energy carriers are present in the HIC, this does not mean that all conversion and storage technologies can be applied in the HIC Rotterdam. The exclusion criteria, listed below will narrow the presented lists of technologies.

- Electricity input
- TRL
- Capacity
- Scalability
- Safety
- Electricity generation
- Efficiency

Electricity input
The conversion technologies that require electricity as input are e-boilers and electrolysers, as shown in Table 5.3. The current capacity of e-boilers and electrolysers in the HIC Rotterdam is negligible. Electrolyser farms under construction are all planned on the Maasvlakte in the HIC Rotterdam. As the Maasvlakte is not within the congested area, electrolysers located here are not able to alleviate grid congestion in the other parts. There is an electrolyser pilot project in Rozenburg, within the congested area, converts electricity to hydrogen that is then used to heat homes [177]. This pilot project is however not suitable for a scalable solution within the HIC Rotterdam. Another electrolyser installed within the HIC Rotterdam is at the Nobian site. This installation uses its flexibility to trade on the imbalance market [65]. Installing additional electrolysers with the aim to provide congestion management is currently not possible since a grid expansion would be necessary before an electrolyser could be installed. The same holds for e-boilers and industrial heat pumps, as they require a large grid connection which is not available as of now. Their development is expected to take off from 2030 onwards [159].

Excluded: electrolyser, e-boiler, heat pump

TRL
From the list of available conversion technologies a significant share is dropped due to the immaturity of the technology. RIFT is one of the technologies still in the early phases of development and therefore not available in sufficient capacity on industrial scale to be included as a potential energy hub component. The same holds for upcoming hydrogen production technologies, methane pyrolysis, and thermochemical water splitting. When talking about renewable generation, technologies that come to mind are usually wind, solar, geothermal or hydropower. Though water holds more potential for energy generation than just in the form of hydropower, for example by utilising temperature differences using OTEC, these technologies are also still in the early stages of development. Furthermore, certain heat-to-power technologies, while useful when combating grid congestion, will not meet industrial needs in

the foreseeable future. Fuel cell technology is currently in operation at industrial scale. However, this technology has several variants. Only solid-oxide (SO FC) and polymer electrolyte membrane fuel cells (PEM FC) are starting to be adopted in pilot projects. However, this technology still has a way to go as currently only 230 MW of stationary capacity is installed in Europe [13]. The same holds for gas turbines that are retrofitted to be fuelled by low-carbon fuel ammonia. The first two turbines worldwide are currently in development. These will likely be available in Europe by 2030, when grid congestion in the HIC Rotterdam is projected to be resolved already [183, 23].

Excluded: fuel cells, methane pyrolysis, TSCW, RITO, RED, RIFT, wave energy, tidal energy, OTEC, ammonia turbine

Capacity
Following the 1 MW minimum, the piezoelectric generator is dropped from the list of potential energy hub components. For the case of the piezoelectric generator it is typically used in small scale applications due to its specific properties. The technology can create electricity from pressure or vibration. The generator is however limited by the mechanical stress levels the material can endure before breaking. Examples of applications are wearable devices, remote controls or monitoring equipment [102].

Excluded: piezoelectric generator

Applicability in HIC
While multiple plants in the HIC Rotterdam produce high-temperature (HT) heat (>100°C), it is typically recycled cascadingly in other processes nearby. The HT heat potentially available for power generation comes from only a few sites in the HIC Rotterdam (personal communication, 2023). HT heat is thus not abundantly available, making it unsuitable for a scalable energy hub solution.

Excluded: high-temperature ORC

Electricity output
When examining the remaining conversion technologies, there are processes that do not directly generate electricity. These include pyrolysis, anaerobic digestion, boilers, Haber-Bosch, SMR, and gasification. These processes result in the production of biofuels, syngas, steam and ammonia. Biofuels, syngas, and soon ammonia [23] can serve as fuel for generating steam, which, in turn, produces electricity when connected to a steam turbine. In such cases, the steam turbine acts as the crucial component that contributes to additional electricity supply. The inclusion of these redundant technologies would only escalate costs, as the steam turbine remains the primary source supplying the energy system with electricity. As the focus is on assessing the ability of components to facilitate a flexible energy supply, redundant conversion technologies have been excluded.

Excluded: pyrolysis, anaerobic digestion, boilers, Haber-Bosch, partial oxidation, SMR, gasification, waste incineration

Efficiency
One of the conversion technologies still remaining is the low-temperature organic rankine cycle (LT ORC), however it deals with a low conversion efficiency. Industrial scale installations exhibit efficiencies between 5-8%. Though low-temperature waste heat is abundantly available in the HIC Rotterdam there is already an application for it in the form of multiple heat grids transporting waste heat to the built environment. The efficiency of low-temperature district heating networks is typically 89% [119]. Utilising low-temperature waste heat for electricity generation would therefore seem wasteful if a significantly more efficient alternative is easily accessible.

Excluded: low-temperature ORC

5.2.3. Storage technologies

For storage technologies a list of exclusion criteria is applied as well to find technologies suitable for the energy hub configuration that will be researched in this project. Similar criteria can be applied to storage as to conversion technologies, with the exception of electricity generation as storage technologies imply that energy is extracted in the same form it is absorbed. This leaves the following list of exclusion criteria that will be applied to the list of storage technologies. For storage technologies the same limits are applied which are described in Table 5.5.

- Electricity input
- TRL
- Capacity
- Scalability
- Efficiency

Electricity input
With the focus of this research being remedies for grid congestion all storage technologies that use different energy forms than electricity as in-/output are disregarded. A counter argument against this exclusion criterion could be that other forms of energy storage might reduce the electricity demand indirectly, for example in the case an e-boiler can reduce its operating hours. However, in reality electricity is not yet used for heat or hydrogen demand. Based on this criterion all latent, sensible and thermochemical heat storage technologies as well as chemical energy storage can be excluded for the energy hub configuration.

Excluded: ice storage, cryogenic air, molten salt, hot water, rock cavern. adsorption. salt hydrate, H_2-tank, salt cavern, NH_3-tank

TRL
The Technology Readiness Level of all remaining storage technologies are high. It could be argued that the redox-flow battery is not yet in use on a large scale. This technology is however developing fast and the first installations are now in operation on industrial scale in Europe [110]. The same holds for electric vehicles as energy storage. Currently vehicle to grid is still in development, however an increasing amount of car models support bidirectional charging of the car (V2X), which could be used to power all sorts of equipment [181].

Excluded: -

Capacity
Flexibility services for industrial applications require a significant amount of power. Components requiring electricity generally operate on the scale of kilowatts. For this reason the supercapacitor is excluded from the list of storage technologies. Its cell voltage is low, therefore only a small energy capacity can be achieved. The supercapacitor finds its value in rapid response applications where a high power density is required. To provide an example, supercapacitors can have a power density of up to 10^5 W/kg, where batteries only reach 10^2 W/kg. The disadvantage of supercapacitors comes from the low energy density, in the order of 10 Wh/kg where batteries reach a tenfold [139].

Excluded: Supercapacitor

Applicability in HIC
Pumped hydro and CAES are both technologies that enable storage of large quantities of energy. Pumped hydro storage is a configuration of two water reservoirs at different elevations that can generate power as water moves down from one reservoir to the other, passing through a turbine [131]. This poses the problem for integration into the energy hub configuration, as such an elevated body of water is not present near the HIC Rotterdam. If it were, the size required for a viable installation would not match the scale of the energy hub. Similar arguments can be made for compressed air energy storage (CAES) as an installation at regular size requires a large underground reservoirs to store air, such as an aquifer or depleted gas field. For CAES however there exist small-scale applications. The problems with these configuration are the barrel size required to store the required amounts of energy as well as energy efficiency, 11-17% compared to 70-90% for batteries [32]. Another technology unsuitable for the industry cluster in Rotterdam is SMES. Superconducting magnetic energy storage (SMES) technology has fast response time, sufficient energy and power densities and a high efficiency. However it also has multiple drawbacks, of which high costs are an important reason. Furthermore, a SMES system operates at either -269°Celcius or -196°Celcius. An installation that can maintain such temperatures requires high capital investments. Furthermore, the magnetic fields produced by the technology can affect nearby electronic devices and therefore are often installed at distant sites with proper shielding [114]. Such properties do not fit a dense and developed area like the HIC Rotterdam.

Excluded: pumped hydro, CAES, SMES

Efficiency
Efficiency is already shortly mentioned in the previous paragraph. Here the criterion applies to flywheels, though the technology is not necessarily excluded. The innovative solution can be powered by electricity, is matured and can be designed at sufficient capacity, still it is not regarded as a solution to mitigate peak power consumption for any industry. This is because of its high self-discharge rate, mainly due to aerodynamic drag and bearing friction. The technology therefore finds it use in applications that require a discharge time of seconds or minutes [93]. An example in the port of Rotterdam is at UWT where an electric crane is connected to a flywheel [132]. Whether flywheel technology will be included in the ultimate energy hub configuration will depend on the types of industry from which data will be obtained.

Excluded: (flywheel)

5.3. Cluster composition

From the complete list of potential energy system integration possibilities some are omitted based on the exclusion criteria. The remaining technologies are assessed on their potential. Depending on component inputs or outputs compatible configurations can be made for potential energy hubs in the HIC Rotterdam. Initially, a search is done on potential energy hubs using assets that are already present in the HIC to discover whether synergies can be unlocked. Additionally, components are considered that could transform any industrial cluster into an energy hub when newly installed.

5.3.1. Synergies

An assessment on remaining energy hub features is done based on knowledge gathered in literature and from conversations and interviews with experts from the Port of Rotterdam as well as people working in industry.

Inputs and outputs
Tables 5.6 and 5.7 show the energy carriers that are used as input and output in the HIC. Similarly to the belief of industrial symbiosis as described by prof. Chertow [25], it is interesting to know which outputs are available as waste streams and can potentially be utilised as inputs for an energy hub in the HIC Rotterdam. Utilising waste streams can increase a cluster of companies' energy efficiency, thereby reducing energy needs. This follows from the idea that if a company can utilise available waste streams it might potentially require less electricity for certain processes.

Out of all energy carriers that are consumed syngas, steam, heat and electricity are available in the form of residual streams in the HIC [19, 2, 77, 81, 5, 28, 123, 29, 187, 145, 163, 143, 59]. From these, steam and heat are not usable for industrial parties in the HIC Rotterdam as of now. This is because residual steam in sufficient quantities is already cascadingly recycled, through projects like the Botlek steam network [133]. Furthermore, currently residual heat flows from the waste incineration site is injected into the Rotterdam heat network, which supplies the built environment with waste heat from industries. Other residual heat streams in the area are of insufficient quality to be useful for other industrial parties [58].

To continue, syngas is mostly used for the production of ammonia or methanol and can thus be used as a fuel. Lastly, residual electricity is extremely useful in the face of grid congestion. The sources of residual electricity are CHP-systems, which were referred to as electricity generation units earlier in this chapter. Specifics of these systems will be discussed in the next paragraph.

Conversion
The remaining conversion technologies are steam and gas turbines and internal combustion engines (ICE), all rotary engines. The small size of this list speaks to the issue unfolding in the port area; only little options are found for potential flex capacity, relating back to the issues mentioned in Chapter 4. For the individual machines that are present in the HIC Rotterdam it is not clear what specific type of technology is installed. However, since the operational characteristics and outputs are similar for either a steam, gas turbine or ICE they are grouped as electricity generation units. From the available waste streams, methanol and ammonia can potentially be used as fuel for these generation units. However, at the time of writing only a handful pilot projects are conducted worldwide using ammonia as fuel, indicating the immaturity of the technology [6]. Methanol is similarly still in the development phase.

Though the rotary engines might not be able to benefit from nearby residual streams they might still be valuable in providing flex capacity. Depending on their utilisation rate, the generation units could provide electricity to an energy hub in times of peak consumption in order to relieve the grid. Some of the rotary engines in the HIC Rotterdam are used in combination with a boiler, making it a combined heat and power (CHP) system. The residual electricity mentioned before, comes from these CHP-systems that primarily supply heat but generate electricity as a by-product.

The inclusion of CHP-systems in an energy hub is well researched, as stated by Mohammadi et al. [112] who show CHP-systems are even the most common conversion technology to be included in literature researching energy hubs. An energy hub benefits from conversion technologies which can use an energy carrier to meet more than one demand. This structure results in increasing efficiency and reduction of primary energy consumption and costs. This feature as well as its high energy efficiency makes that CHP-systems are widely adopted in industry.

Currently, electricity generated by CHP-systems in the HIC Rotterdam is delivered to the grid. However, it is worth investigating if these systems can be used the other way around, primarily generating electricity in times of peak demand with heat as by-product. A first step would be to check if these systems are available near congested areas. This will be explored in Section 5.4.

Storage
The storage technologies remaining after applying the exclusion criteria are rarely implemented in the HIC Rotterdam yet. From conversations with industries and experts at the Port of Rotterdam it becomes clear that many companies are now looking into these technologies as ways to increase electricity capacity at times. The conclusion can be made that currently little to no storage technologies are in use in the HIC Rotterdam and can therefore not be utilised for synergies. They do provide however excellent investment opportunities as additional components to a company's current operation. The selected storage technologies will therefore be discussed in the following subsection.

5.3.2. Additional components

Apart from utilising waste streams or interconnecting conversion technologies to establish an energy hub, companies can invest in assets that create flexibility in their processes.

Inputs and outputs
Wind turbines and solar PV systems can provide additional electricity capacity to an industrial cluster. Examples of wind parks can be found at the Maasvlakte 2 and at headland Rozenburg. These sites are secluded and thus do not cause safety hazards in combination with industrial activity. When used however in an industrial energy hub they ought to be closer to the cluster site to limit connection costs. There are locations thinkable in the HIC Rotterdam where wind turbines would fit and be a valuable asset to nearby industries. A port where wind turbines are located within the HIC is the Port of Antwerp. Figure 5.1 shows an image of wind turbines located in between industrial sites in the Port of Antwerp.

Solar PV systems could also provide grid relief, though only during the day. The problem for solar PV is that little space is available to install solar panels. Placing solar panels on top of industrial assets is currently not feasible, which only leaves office buildings as possible area to install solar PV systems.

Conversion
In the search for synergies using conversion technologies rotary engines were chosen as assets to look for in the HIC Rotterdam. Electricity generation units typically operate at scales of tens of megawatts. Nevertheless, smaller units are also available and mostly employed for temporary purposes. A generator set can be as small as 10kW up to 5 MW [130]. When looking for solutions to mitigate grid congestion, such generator sets could provide the necessary capacity to compensate for peak demands that exceed grid capacity limits.

Storage
Lastly, excluding storage technologies based on the criteria described in this section results in a list of technologies that are applicable in an energy hub in the HIC Rotterdam; electric vehicles, Li-ion batteries, redox-flow batteries and flywheel technology. Where flywheel technology can only be applied if it matches the operation of the cluster that will ultimately be modelled. All of these technologies can be sized to a scale where they can positively attribute to an industrial cluster's electricity capacity. The

Figure 5.1: Image of wind turbines located near industrial sites at the Port of Antwerp

previous subsection already mentioned that multiple companies in the HIC Rotterdam are currently looking into the option of installing storage technologies to increase electricity capacity at times. An example of flywheel technology applied in the HIC Rotterdam was already given in [132]. The benefit of the selected storage technologies is that all can be designed modularly to create as much capacity as needed.

5.3.3. Boundary conditions

The first step into discovering potential sites for energy hub integration is completed by identifying what components could help drive this integration. The next step is to identify factors that might obstruct energy hub integration efforts. Literature on energy hub integration and industrial symbiosis is reviewed on potential barriers, while research on (pilot) projects in the Netherlands sheds light on challenges currently faced. Multiple factors are compiled that might prevent the successful implementation of an energy hub. Some of these factors are strict criteria that need to be met, others are simply deemed undesirable.

Same 'ring'

From conversations with grid operators and people working in the industry it became clear that a strict requirement for energy hub integration is that companies must be connected to the same 'ring'. Meaning that companies wanting to start an energy hub can only do so if they are physically connected to the same set of power cables transmitting electricity from a single substation at a single grid level. In a highly complex grid like the one in the HIC Rotterdam, shifting loads between different grid levels might result in undesirable side-effects. Load reduction in one part of the grid can lead to an increased load elsewhere in the grid. This phenomenon occurs because electricity, just like water, follows the path of least resistance. When loads are balanced within a single grid level however, other parts of the grid are not affected. For this reason, grid operators in the Netherlands are determined to only support the development of energy hubs on the same 'ring' (personal communication, 2023). In order to know which companies are eligible for energy hub integration the grid topology in the HIC Rotterdam needs to be examined. Grid operators have mapped their respective grids in [66] and [154]. While the maps give a good overview of the grid topology within the HIC Rotterdam, the maps lack detail to confirm whether companies are connected to the exact same grid level. An indication can be made by dividing the area based on 150kV grid zones in which companies likely can form an energy hub. The result is shown in Figure 5.2 where blue dots represent 150kV substations and each 150kV grid zone is indicated by a dashed blue line. A detailed version of this map can be found in Appendix B.

Figure 5.2: Overview of 150kV grid zones in HIC Rotterdam

No must-run (CHP)
Components that are potentially utilised to unlock synergies have the requirement to operate flexible, as opposed to 'must-run'. In the HIC Rotterdam, only CHP-systems that do not operate at baseload are suitable for energy hub integration. Research by DNV Netherlands states that more than half of CHP-systems in the Dutch industrial sector operate as must-run [21]. In the mapping exercise will be researched whether sufficient systems are located in the area of interest to use CHP-systems in the energy hub configuration that will be modelled.

Minimal dependency
A softer criterion is that all companies involved should refrain from becoming dependent on the energy hub. This can happen if a single large company becomes the sole supplier of a certain resource to other connected parties. If the revenue that is generated from the sale of this resource of the large company is insignificant in its total revenue there is no incentive for the large company to act in the benefit of the smaller companies. Minimal dependency is thus desired between companies within the cluster. If dependencies do exist, the inter-dependency should remain balanced. For the HIC Rotterdam it is observed that industrial symbiosis originates with the prerequisite of a similar inter-dependency, among other factors (personal communication, 2023). This philosophy aligns with the critical success factors described in the MOOI EIGEN blueprint for energy hub implementation [18], mentioning minimal dependency and the energy hub's ability to withstand the exit of one or more parties.

Flex capacity and/or complementary loads
Another desired feature for the integration into an energy hub is the availability of flex capacity within the proposed cluster of companies. The idea behind this is that the advantage of an energy hub is the higher utilisation of flex capacity. If a flexible asset can be used to mitigate peaks from multiple companies instead of just a single one, more benefits can be gained for the load on the grid. As described in Chapter 4 many of the industrial activities in the area operate at high baseloads. Therefore, little flex capacity is present within the HIC Rotterdam. Without the availability of flex capacity energy hub integration can however still be valuable if load profiles of companies willing to collaborate are complementary. Meaning that moments of peak electricity consumption do not collide and synergies can be unlocked by aggregating load demands. The potential for these synergies will have to be analysed based on the obtained load demand data, this will be done in Chapter 6.

5.4. Mapping and data request

Following the analyses conducted in this chapter multiple factors are identified that are necessary for an energy hub in the HIC Rotterdam. Electricity generation units can provide local flex capacity, if the system is connected at the same grid level and is not operated in 'must-run'. From TNO's MIDDEN reports a list can be compiled of all electricity generation units located in the HIC Rotterdam. In Figure 5.3 the generation units are mapped in the 150kV grid zones, Table 5.8 displays the operator, the unit's power rating and the voltage level at which the unit is connected.

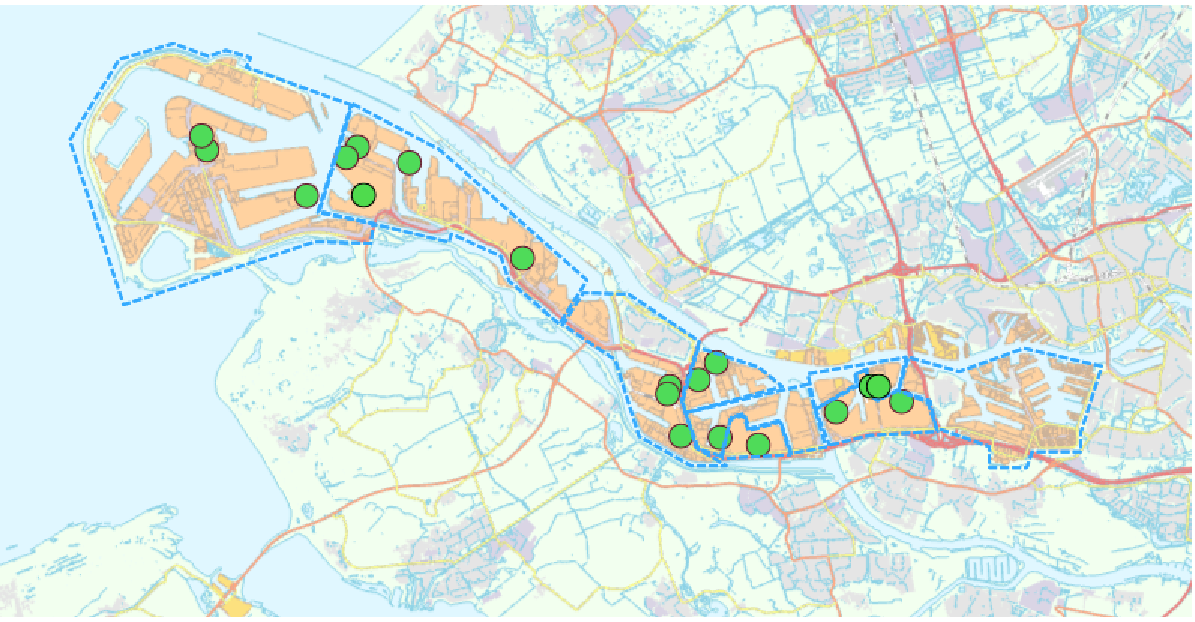


Figure 5.3: Electricity generation units and 150kV zones mapped in HIC Rotterdam

Table 5.8: List of electricity generation units within the HIC and their power ratings

Operator	Power rating [MWe]	Voltage level [kV]
Uniper	1070	380
Uniper	79	380/25
Riverstone	731	380
Eneco	870	380
Indorama	24	25
BP	214	150/25
ADM	(unknown)	25
Alco Energy	48	25
Air Liquide	300	150
Air Liquide	88	150/25
Air Liquide	48	150/25
Air Products	96	25
AVR	140	25
Cabot	12	25
Nobian	51	150/25
ExxonMobil	140	150/25
Shell	367	150/66/25
EPNL	810	380
EPNL	426	150

In Chapter 4 the state of grid congestion in the HIC Rotterdam is analysed. One of the outcomes of the chapter is that the areas Europoort, Botlek and Pernis are currently labelled as congestion area, therefore no grid connection requests can be honoured in these areas. Companies in these areas benefit most from a solution that can create additional electricity capacity. When only taking into account the units located within the congested areas, as defined in Chapter 4 the list of generation units is refined by excluding the units highlighted in lightgray in Table 5.8. Table 5.8 also shows the voltage level at which the units are connected to the electricity grid. Most of the units are connected at the 25kV level. This is the level at which most companies in the HIC are connected. Integration into an energy hub would thus be possible for the electricity generation units that are connected at 25kV. For the units connected at a different level additional transmission cables need to be constructed would they want to supply local flex capacity.

While the mapping exercise shows that integrating a rotary engine into an energy hub is a scalable solution within the HIC Rotterdam, it still provides only a single opportunity. It is clear that in the HIC Rotterdam little further options are found that facilitate energy hub integration. Despite little options, all people working on grid congestion and energy hubs agree on the same statement; the factor most influential in the development of an energy hub is the drive and willingness of people to make an energy hub into a success. The message here, is that if companies are willing to work on collaborative solutions there is a lot that can be accomplished. While the availability of a generation unit helps to unlock synergies, collaboration in an energy hub allows for joint investments into solutions if such assets are not readily available. In addition, the collaborative approach of an energy hub can in itself help to balance complementary loads. This line of thought leads to the data request being sent to a broader group of companies. The data request is sent out through the extensive network of the Port of Rotterdam. Efforts are made to get in contact with electricity generation operators from Table 5.8, additionally terminals and chemical plants are approached.

5.5. Data request and configurations

The data requests resulted in obtaining electricity load profiles of four distinct terminals. All four terminals are tank terminals, or 'liquid bulk' terminals. Though these are all of the same type, it is one of the most common types of enterprise in the HIC, since many of the area's companies are terminals (+/- 60) of which the largest share are liquid bulk terminals (25) [40]. In Section 3.3 two different approaches towards the design of the energy hub configuration were described. Since the obtained data describes a single type of industry, the approach using a single energy hub design is adopted. For this configuration, various degrees of electrification and system integration can be compared.

Configuration

Following the data acquisition, the cluster that will be modelled consists of four tank storage terminals. To be able to describe the operation of the cluster, interviews are held with the respective terminals of which data is obtained. Since the aim of the model is to describe any tank storage terminal in the HIC Rotterdam, desk research is done on the operational characteristics of tank storage terminals [38, 141, 57, 182, 174, 108, 178]. This research is supplemented by interviews with sector experts at the Port of Rotterdam. From the study on tank terminal components a list can be made of components that make up a terminal's electricity load. This list is presented in Table 5.9.

Table 5.9: List of components that make up a terminal's electricity demand

Component	Description
Loading pumps barge	Pumps used to load barge with product
Loading pumps SGV	Pumps used to load SGV with product
Tank mixers	Mixers in tanks to maintain desired product properties
VRU	Unit that captures evaporated gases from storage tanks
Nitrogen blanketing barge	Equipment used to supply inert gas into tank
Nitrogen blanketing SGV	Equipment used to supply inert gas into tank
Compressors	Equipment used to transfer product between tanks and regulate pressure
Office	Office lighting, heating, cooling, other electric equipment
Lighting	Site lighting

SGV = Sea-going vessel, VRU = Vapour recovery unit

In the component list a distinction is made between pumps and nitrogen blanketing for barges and sea-going vessels. This is because the electricity demand from equipment for sea-going vessels is much higher compared to equipment used to serve barges. The weight carried by a vessel is generally expressed in deadweight tonnage (DWT), a measure of how much weight a ship can carry. The DWT of a barge is typically 1,000-5,000 compared to 10,000-50,000 for an SGV (analysis from [171, 149]. The same holds for vessels that require nitrogen blanketing. As stated in Table 5.9 nitrogen blanketing is the procedure of supplying an inert gas into a storage tank. The inert gas forms a 'blanket' over the product thereby preventing the product from oxidising, often nitrogen is used. A vapour recovery unit (VRU) can be used for multiple purposes. The primary one being the prevention of toxic gas release into the atmosphere and the capture of valuable evaporated gas for subsequent condensation and return to the tank. It should be noted that not all tank terminals have all of these components installed. The list rather shows the potential set of components that a tank terminal can install on their site.

5.5.1. Future potential

The motivation for this research is the grid congestion currently faced in the HIC Rotterdam. The aim of this research however is to evaluate how the electricity demand of an industrial cluster develops over time based on uncertain influences and choices made by the cluster itself. In this context an effort is made to include technologies in the model that might only come into use in a few years time, as these might influence the cluster's operation towards 2050. The problem with this approach is that no assessment can be made of technologies that are still in the early phases of development, as it is not yet clear what capacities the technology will be able to provide or even its specific use case. An even bigger gap in knowledge exists for technologies that are not invented yet. When the timeline spans multiple decades it is likely that new technologies will be invented that can not be envisioned as of now. These 'unknown unknowns' are a fundamental limitation in the method of exploratory modelling. Remedies for these limitations are discussed in Chapter 8 on modelling. This subsection discusses technologies that could mature in the near future as information is required on their operation to be included in the energy hub configuration.

Inputs and outputs

The development of solar PV systems has resulted in a decrease in panel prices [151]. As panel prices are now at the point where solar PV is competitive compared to other forms of energy generation, development will potentially focus on a wider range of applications. Following this thought, it can be assumed that in the future solar panels can be placed at currently unsuitable locations.

Conversion

For conversion technologies multiple developments are anticipated. The selected technology, rotary engines, can expect to be fuelled by alternative resources in the near future. As mentioned before, ammonia and methanol fuelled gas turbines are currently in development [183]. Moreover, hydrogen might be increasingly used as fuel driven by decarbonisation efforts. Currently, certain gas turbine models are already capable of running on hydrogen, though the hydrogen economy is not developed enough to sustain a fully hydrogen-driven operation [68].

A conversion technology that could give a boost to the hydrogen availability is the electrolyser. The technology is excluded based on its low maturity level, which will most likely change in the future. An electrolyser benefits from a high utilisation rate to make it viable. High rates of renewable energy supply would therefore be a good match for an electrolyser. But since a tank terminal is not focused on generating renewable energy as part of its operation, electrolyser technology is assumed to be too distant to the terminal's core operation to be included in the configuration.

Fuel cells and generators might be valuable additions to a tank terminal's operation by supplying additional electricity capacity. In the face of grid congestion, these will need to be considered in the electricity system model when simulating the terminal's future operation.

Storage

The same holds for batteries, which can provide the cluster with additional electricity capacity at times of peak demand. A limiting condition for the implementation of a battery system would be the duration of peak loads. Since batteries have limited energy capacity they can only supply additional power for a certain period, depending on the size and energy density of the battery.

6
Data analysis and sizing

In this chapter the profiles will be visualised and put into context. For the components that can potentially be added to the terminal an optimal size will be calculated according to performance ratios described in literature.

6.1. Description

In the previous chapter the cluster selection procedure is described. The outcome of this procedure has been a single type of industrial cluster to focus on. The requests resulted in obtaining electricity load profiles of four different tank storage terminals. The electricity demand of a liquid bulk terminal is mainly tied with the amount and frequency of ships that moor at the terminal. The majority of the electricity demand comes from pumps transporting goods from ship to tank and mixers making sure the liquid bulk maintains the right properties (personal communication, 2024). This relation for the electricity profile is also found at other types of terminals that experience high electricity demands from (un)loading ships at berth. At a high resolution (e.g. seconds,) different types of terminals may show differences in their load profiles depending on the specific model of cranes, conveyor belts and pump systems, however at a 15-minute time interval the profile characteristics are similar. The obtained datasets can therefore be assumed to be representative for a terminal in the HIC.

As mentioned before, four electricity load profiles have been obtained from four distinct terminals, described as terminals A, B, C and D. Each dataset contains the measured load at the electricity grid connection. For terminals B, C and D this is measured every 15 minutes, for Terminal A every hour. The three terminals supplied data measured over two years, 2021 and 2022. The Terminal A over a single year, 2021. The datasets therefore contain 70,080 and 8760 data points respectively. To be able to compare the load profiles and sum them the choice is made to extrapolate the data of Terminal A so that a 15-minute resolution is obtained as well. An example of the terminal's load profile on a random day in the year is provided in Figure 6.1. When obtaining the data there is no information provided on the power or energy capacity of assets located at any of the terminals.

To process and analyse the datasets, the data is loaded into Python where the date and time columns are formatted to all describe timestamps in an identical way. Since the data presents measurements of the amount of electricity used every 15 minutes (in kWh), the values are multiplied by four to represent the average quarterly electricity load (in kW).

6.2. Insights and component sizing

After preprocessing, the data can be analysed to gather useful insights. Different configurations are analysed and compared to the base case, where each configuration consists of the components in the base case complemented by additional components.

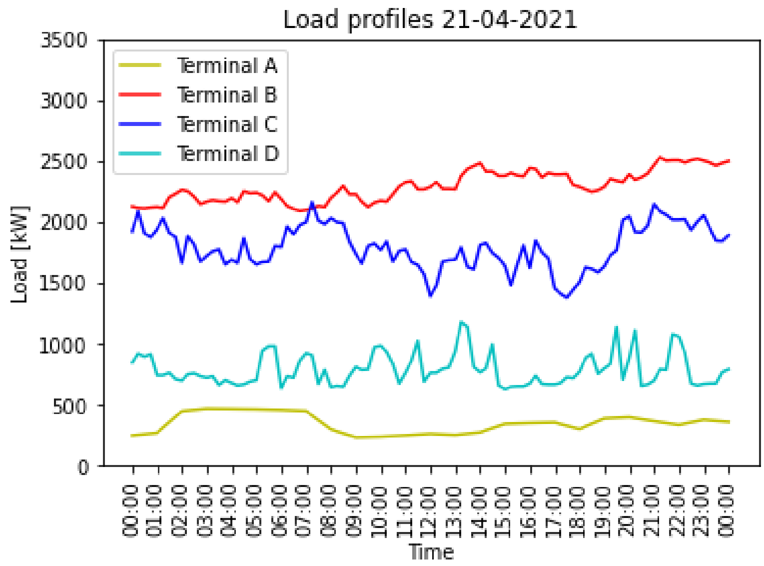


Figure 6.1: Example of load profiles of the four terminals, shown for 21-04-2021

6.2.1. Base case

The first configuration that will be outlined is the base case, which will be used as reference for the other configurations. In this configuration no changes to the energy system are made. The maximum electricity loads P_{max} of the terminals are presented in Table 6.1.

Table 6.1: Maximum annual load of terminals A, B, C, D and their sum

Terminal	Maximum annual load [kW]
A	1604
B	3316
C	3336
D	1560
Sum	**9816**

Battery

A battery has two characteristics that are of importance in this research, the power rating (P in kW) and energy capacity (E in kWh). When installing a battery for congestion management the power rating determines how much power it can provide, as supplement to or substitute for the power grid. The energy capacity states the duration for which it can provide this power. For example a 100kW/200kWh BESS can supply 100 kW of power for 2 hours, since it contains 200 kWh of chemical energy. For every terminal an optimal battery size is calculated. This is done by examining the required energy capacity for a range of power capacities. This range spans between 100 kW and 2 MW, with a resolution of 100 kW since a higher resolution will not have significant impact on the outcome and because battery packs of this size scale approximately per 100 kW as well. The energy-to-power (E/P) ratio is capped at 8 as this is typically the maximum E/P ratio mentioned in literature. The capacity that can be freed per terminal is listed in Table 6.2 below.

Terminal	Power [kW]	Energy [kWh]	E/P ratio [-]
A	500	3750	7.5
B	500	2000	4
C	500	2250	4.5
D	700	4900	7

Table 6.2: Optimal sizing for BESS per terminal

The E/P ratios are rounded to 0.5 and sized so that the energy capacity is sufficient for the calculated maximum energy demand. For the energy capacity of the batteries the largest capacity is assumed that had a E/P ratio of 8 or lower. A higher energy capacity will allow the operator to increase the earnings when it can be used for arbitrage or balancing after 2030.

Generator / Fuel cell
For a generator or fuel cell there is no limit to the energy it can provide, assuming fuel supply is not an issue. A calculation similar to the one used for the battery sizing can therefore not be made. The size of a generator set instead depends on the capacity that is needed for an envisaged expansion or electrification. The maximum generator size that can be leased is generally around 5 MW [130], however multiple generator sets can be installed to increase capacity. In Appendix C higher power capacities are described for the rotary engines, these however often relate to stationary installations. While for the energy hub's described in this research a generator set is assumed that can be leased in comparison to a generator that is an integral part of a companies' operation.

The advantage of a generator compared to a BESS is its unlimited energy capacity. Where a battery can provide only its total charge, a generator can operate continuously. The downside of a generator however is that it has a minimum power rating. If electricity demand decreases below the minimum power requirement the generator starts to deliver back to the grid. In the case there is no contract agreed for supply to the grid, this will result in heavy fines. Even though the model does not account for costs it is good to keep this in mind.

Electricity generation unit
To size the electricity generation unit, one can refer to the list of units present in the HIC Rotterdam. From the selected generation units, it is crucial to determine the available capacity for supplying flex capacity, which can be determined by examining their actual power output. As mentioned before, 'must-run' units cannot provide flexibility as they already operate at maximum capacity most of the time. The European organisation for grid providers publishes data on some of the generation units that are connected at the 150 and 380kV levels. For the Eneco generation unit (Enecogen), one of the Air Liquide units (Pergen) and both EPNL generation units (MaasStroom and Rijnmond) data is available on their actual power output. Figure 6.2 shows their power output for a week in March 2024. Scrutinising the power output of the four systems shows that similar profiles are found throughout the year.

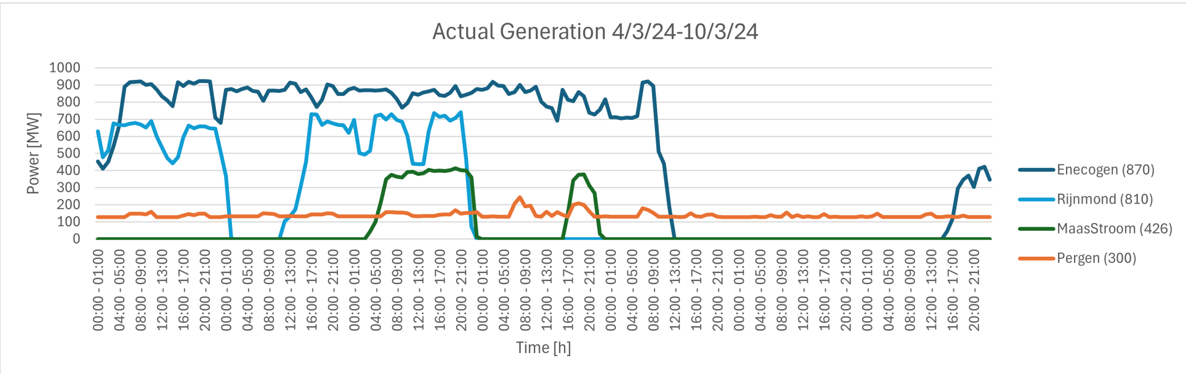


Figure 6.2: Actual generation of electricity generation units in the HIC between 4/3/24-10/3/24

The electricity generation units are rated at 870, 810, 426 and 300 MWe. Note that the rated power is not the maximum power that can be delivered as can be seen by the power output of the Enecogen plant. A generation unit can nevertheless only operate above rated power for a limited amount of time. What becomes clear from Figure 6.2 is that there is still a lot of capacity left to use. The Enecogen, Rijnmond and MaasStroom plants sometimes operate at high power outputs, but this is only for a limited amount of time. The Pergen unit seems to be 'must-run' however when scrutinising the power output it seems that only half of its rated power is required for baseload operation. The other 150 MW is almost never called upon. There is no public data on the power output of the other electricity generation units in the HIC, but industry experts within the Port of Rotterdam agree that for the other generation units a lot of capacity is currently unused as well.

As the goal is to design a scalable energy hub solution, the unit with the smallest power capacity is used as reference. This is the steam turbine from Cabot with a power rating of 12 MWe. This ensures that the results from the designed solution would at least be similar or more beneficial if other electricity generation units would be integrated. Moreover, when referring to the load profiles in Figure 6.1 the sum of capacities would sum to about 5000 kW. Even the smallest electricity generation unit would thus be able to supply sufficient power for the cluster's current operation. Even if this were to increase in the future, there would still be about 7 MW left for the cluster to utilise. Important to note is that for the larger installations it is possible to run at a lower capacity. Even for the largest installations present in the HIC Rotterdam it is possible to operate at a pilot light which would generate sufficient power to provide to a nearby cluster.

Solar PV

For solar PV two different situations are assessed. First, the available area for the installation of solar panels is calculated with current placement standards in mind. This results in the only area available for solar panels being the rooftops of office buildings. For the second situation it is assumed that solar PV technology has developed so that panels can be installed on top of storage tanks as well. For each terminal the approximate area available in both situations is presented in Table 6.3. In Rotterdam in 2021 the average daily peak solar irradiation power was 435 W/m^2 [31]. For the power calculation a 20% solar panel efficiency is assumed.

Table 6.3: Available area for solar PV for each terminal in every situation and corresponding peak power output

Terminal	Area 1 [m^2]	Area 2 [m^2]	Peak power 1 [kWp]	Peak power 2 [kWp]
A	500	10,000	217.5	4,350
B	1000	80,000	435	34,800
C	800	50,000	348	21,750
D	1500	100,000	652.5	43,500

Wind turbine

Another renewable energy system that can provide electricity is a wind turbine. The turbine model chosen to include in the system model is the Vestas 112-3.45. This wind turbine model is already in operation in the HIC Rotterdam at the Slufterdam [129]. Also, the wind turbines installed in the Port of Antwerp have a similar size which indicates the feasibility of the model for use in a port area [172, 150]. The rated power of the turbine is 3.45 MW. For the electricity system model it is assumed that a maximum of two wind turbines can be installed on the cluster's site.

Microgrid

Apart from installing additional generation or storage capacity on individual companies' sites it is interesting to check what happens when the load profiles of the four terminals are aggregated. As discussed in Section 1.3 a cluster that has interconnections between the different electricity systems is called a microgrid. The advantage of this configuration is that an aggregated electricity profile can balance the peaks and valleys of individual prosumers. This results in multiple benefits, of which the first is a decreased maximum load. This effect is illustrated in Figure 6.3, where it can be observed that peak loads do not occur at the same time between terminals, resulting in the maximum aggregated load being lower at all times than the sum of all peak loads. The maximum combined annual load is compared to the theoretical peak load in Table 6.4. Here the same effect is observed.

Another benefit of aggregating load profiles is the enhanced predictability. In other words, a decrease in volatility of the load profile. The reason why this is beneficial is because grid operators build models to predict load behaviour. If the volatility of a load decreases, it becomes easier to predict. Furthermore, when implementing a microgrid a service provider is often appointed to balance system loads. If such a provider can guarantee a maximum load, lower than the sum of individual transmission agreements, a lower transmission fee can be negotiated. Another advantage for participating companies lies in reduced investment costs for additional capacity. This will be explained in the following paragraph.

The effect shown in Table 6.4 corresponds to the effect of the coincidence factor, a formula described in the field of power electronics to indicate the relation between theoretical and experienced peaks. The formula is presented in Equation 6.1 below.

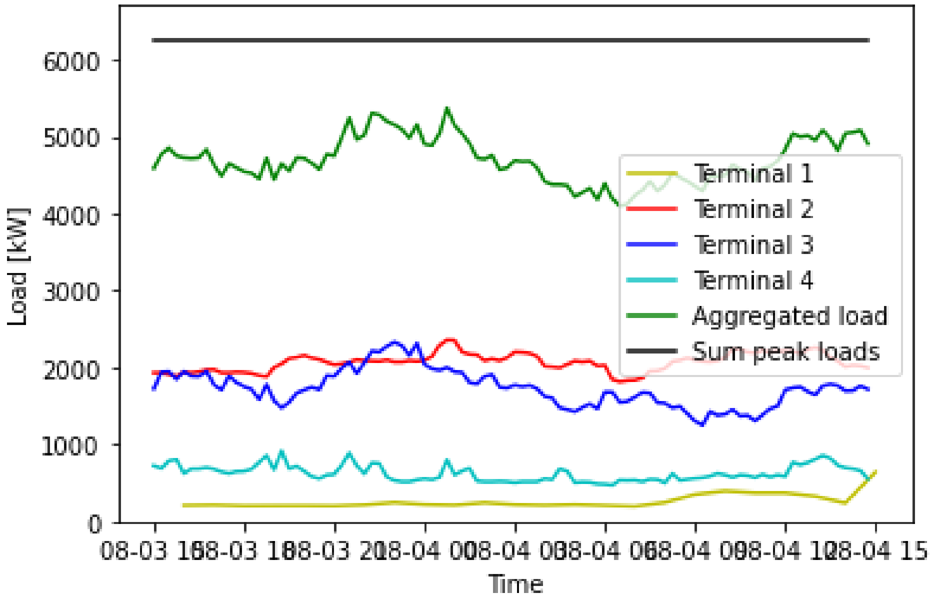


Figure 6.3: Load profiles showing the aggregated load is lower than the sum of peak loads

Table 6.4: Maximum, minimum load and operating range of individual terminals, their aggregated load and the sum of all loads

Terminal	Max load [kW]	Min load [kW]	Range [kW]
A	1604	143	1461
B	3316	400	2916
C	3336	840	2496
D	1560	0	1560
Sum	**9816**	**1383**	**8433**
Aggregated load	**8068**	**2283**	**5785**

$$g_n = \frac{P_{max,n}}{\Sigma_{i=1}^{n} P_{max}(i)} \tag{6.1}$$

The effect of the coincidence factor is that the total peak load of a number of loads is less than the sum of their individual peaks, due to the fact that the individual peaks do not appear at the same time [62]. The factor can be derived from measured load data and is used by DSOs to estimate the peak load for new connections, among other methods. By applying the coincidence factor in grid expansion planning, more load can be connected to the same infrastructure. For our case study the coincidence factor is equal to 0.82, following Equation 6.1. This corresponds to the norm often used for industry of 0.8 [115]. The amount of capacity that would become available by simply pooling the connections amounts to **1748 kW**, for the provided datasets.

Since grid operators already use (methods derived from) the coincidence factor, this capacity would not entirely be available. However, if a service provider would ensure that a certain limit is not exceeded, grid operators would not have to account for scenarios where all companies would require their peak demand at the same time. Extra capacity could become available if companies can schedule their operation to fill in each other's peaks and valleys.

As mentioned earlier, the data does not contain information on which assets require electricity at every point in time. Thus, no conclusions can be drawn about the flexible capacity. Interviews with terminal operators however confirmed that little to no flexibility is available at the terminal as the operation is entirely determined by the arrival and departure of ships. The load can therefore be assumed to be fixed for this analysis. The 'microgrid' configuration is thus limited to aggregation of the load profiles as there is no flexibility to exchange within the cluster. Still even without this flexibility the microgrid configuration poses benefits to the DSO as safety margins for a group connection will be lower than the sum of the safety margins for individual connections.

Combinations
The analyses on the benefits of the varying configurations all show the system solutions can prove beneficial to the industrial cluster. Since the industrial cluster is not limited to implementing a single solution it is interesting to research the outcomes of combinations of energy system solutions. One of the benefits of setting up an energy hub, apart from load balancing, is the possibility to collaboratively invest in additional components. From the analysis previously in this section the sum of peak loads for the cluster amounts to 9816 kW. Without further knowledge on the transmission agreements between the terminals and the grid operator it is assumed that the contracted transmission capacity (GTV in Dutch) is equal to this sum. If all four terminals would install a battery system they could free up to 2200 kW of electricity capacity by peak shaving, as stated in Table 6.2. The same calculation is performed for the aggregated load profile and shown in Table 6.5.

Table 6.5: Optimal sizing for BESS for interconnected cluster

Load	Power[kW]	energy [kWh]	E/P ratio [-]
Aggregated	1700	12,750	7.5

A battery system could be installed with a power rating of 1700 kW. Adding this to the capacity made available by aggregating the terminal's loads of 1748 kW results in **3448 kW** of additional capacity by pooling loads and a mutual investment in battery capacity. As both the power and energy rating for the battery in the cluster situation are lower than the combined power and energy rating of the battery investments for the individual terminals (1700kW/12,750kWh vs 2200kW/12,900kWh), a lower average investment is required per company. From this analysis the conclusion can be drawn that through a collaborative investment more capacity can be created for a lower price compared to when companies would invest individually. Similar conclusions are expected for other additional components, as economies of scale help to decrease investment costs.

7

Scenario design

In this chapter an outlook is designed on possible developments that could influence the industrial cluster. The outlook is described in a set of scenarios, made for the group of tank terminals that formed the output of the selection procedure in Chapter 5. Desk research and workshop sessions have been fundamental in the creation of future scenarios. The procedure used for the scenario design is described in Section 7.1. The first step in the procedure, establishing the relevant external and internal factors is presented in Section 7.2. The subsequent parametrisation of these factors is discussed in Section 7.3.

7.1. Design procedure

The methodological approach described in Section 3.5 prescribes the formulation of the XLRM segments before constructing the energy system model. The model can then be structured according to the relations (R) between the system components. The metric (M) shows the overload of the system as a result of the energy hub configuration in every scenario.

7.1.1. Objective

The aim when designing this scenario space is to fulfil two key objectives. Initially, the scenario space should facilitate an in-depth exploration of the overload development for the cluster's electricity system. This exploration is pivotal for generating data that highlights the influence of energy infrastructure on potential evolutionary pathways for the energy system. Secondly, the scenario space design is intended to serve as a robust platform for stress testing an investment path across a diverse set of scenarios.

Within the scenario space, each scenario represents a plausible future state of the energy system. A sampling method is applied to systematically generate sets of scenarios from the scenario space that capture the inherent uncertainties of energy infrastructure planning, while minimising computational effort.

7.1.2. Design principles

In addition to the procedure followed according to the 'XLRM'-framework, the following principles guided the design process. Here inspiration is drawn from the Gridmaster project [184]:

1. The scenario space is designed to include a range of plausible scenarios, each depicting a distinct future state of the energy system. The current energy system is taken as the reference case and each scenario describes a unique state of the energy system in the future
2. External factors serve as the building blocks of the scenario space. Each external factor represents uncertain parameters influencing the evolution of the considered energy system. The values assigned to an external factor dictate the evolution of parameters of the energy system
3. A single scenario is generated by selecting a single value for each external factor from which the scenario space is built

4. Values for every external factors should be independently combinable, meaning that every combination of individual values from every external factor should lead to a unique scenario
5. The complexity of the scenario set should be minimised as to limit the computational effort required. Values for external factors should thus be carefully selected

7.2. Internal and external factors

Internal and external factors can be described altogether due to their similarities. Though perceptually different, their implementation in the model is similar, this will be explained in the next chapter. Furthermore, whether certain factors are perceived as internal or external might be ambiguous. For example the integration of an electricity generation unit can be perceived as either an internal or external factor, depending on if the choice for integration is regarded to be made by the cluster or the unit operator. For clarity, a distinction is made in both factors in their further elaboration.

From desk research a list of external and internal factors is created. An effort is made to be as extensive as possible. Desk research is however regarded to give an incomplete outlook on developments as outlooks on future system states are often regarded as market-sensitive information and therefore not publicly available. Experts on tank storage terminals working at the Port of Rotterdam are therefore consulted on their outlooks for internal and external factors through two workshop sessions. The output of both the desk research and the workshops is presented below. While both lists were originally more exhaustive, refining the list to make it mutually exclusive resulted in the lists presented in Table 7.1 for the internal factors, Table 7.2 describes the external factors that are believed to possibly influence the cluster's operation.

Table 7.1: Internal factors

Nr	Internal factor	Parameter
1	Expansion of terminal capacity	$n_{\text{compressors}}, n_{\text{mixers}}, \ldots$
2	Product diversification	$n_{\text{compressors}}, n_{\text{VRU}}, n_{\text{nitro}}$
3	Efficiency improvement of terminal assets	$P_{\text{pumps}}, P_{\text{compressors}}, \ldots$
4	Number of quays / jetties	$n_{\text{berths, barges/SGVs}}$
5	Alteration climate policy goals	$n_{\text{E-boiler}}, n_{\text{shore, barge/SGV}}, \ldots$
6	Electrification heat demand	$n_{\text{E-boiler}}$
7	Installation battery system	n_{battery}
8	Installation generator set	$n_{\text{generator}}$
9	Installation ammonia turbine	$n_{\text{generator}}$
10	Installation fuel cell	$n_{\text{generator}}$
11	Installation shore power barges	$n_{\text{shore, barge}}$
12	Installation shore power SGV's	$n_{\text{shore, SGV}}$
13	Installation truck chargers	n_{truck}
14	Installation EV chargers	n_{EV}
15	Installation solar PV	$n_{\text{solar PV}}$
16	Installation wind turbines	n_{wind}
17	Inclusion of additional terminal	$n_{\text{terminals}}$

7.3. Parametrisation

After compiling a comprehensive list of factors that could potentially impact the operation of the terminals, the next step involves translating these factors into parameters capable of describing their effects within the electricity system model. It is important to note that at this stage of the project, a start was made at developing both the load and electricity system models. The relationships (R) within these models are described by programming the characteristics of the cluster's components. This programming step is essential as it facilitates the translation of internal and external factors into model parameters during the parametrisation process. Further elaboration on these models will be provided in the subsequent chapter. For the sake of coherence and clarity, the decision has been made to present the entire scenario design explanation within this chapter.

Table 7.2: External factors

Nr	External factor	Parameter
1	Expansion of contractual transmission capacity	P_{grid}
2	Expansion of physical transmission capacity	P_{grid}
3	Connection to electricity generation unit	P_{elec}
4	Connection to heat network	$P_{E\text{-}boiler}$
5	Developments auxiliary equipment	P_{VRU}, P_{other}
6	Change in terminal throughput	$n_{berths,\ barge/SGV}$
7	Diversification traded products	$n_{compressors}$, n_{mixers}, ...
8	Phase out of fossil electricity generation units	P_{elec}
9	Commissioning of grid expansion HIC	P_{grid}
10	Growth electricity demand HIC	P_{grid}
11	Change in safety requirements	n_{VRU}, n_{other}
12	Change in ships cargo volumes	P_{pumps}

The parametrisation is mostly done through desk research, for certain parameters for which the operation is only marginally discussed in literature the workshop sessions proved valuable input. In Tables 7.1 and 7.2 the parameters that translate factors to choices in the model are described. For some factors it is more obvious how to incorporate them in the model than for others. Through the process of parametrisation it became clear that the lists of factors could be more comprehensive. Some factors might describe the same behaviour when expressing them as parameters. For example the expansion of terminal capacity or product diversification. While these are entirely different enterprises a terminal can execute, they might effect certain components in a similar way. Moreover, for certain additional components, Section 6.2 already described that for instance a generator and fuel cell are similar enough in their operation to be described by a single component script. Furthermore, both tables show that some factors affect the amount of components present in the system and others the power rating. This is mostly due to the way internal and external factors are initiated in the electricity load model. For others it is due to the specific factor.

Subsequently, parameters are quantified in order to evaluate them over different scenarios. Depending on the parameter, integer or boolean values were chosen as simulation values. For others a range of values is chosen in which the system is believed to possibly operate in a future state. The development of the parametrisation and quantification can be found in Appendix E. The outcomes can be found in the code used to simulate the scenarios shown in Appendix H. Reasoning for the values chosen can be found in Appendix F. During the workshop sessions a discussion was held on future pathways to explore as evaluation of the created scenario space. An elaboration on this evaluation is presented in Chapter 9.

8

Model of an Energy Hub

After selecting an energy hub configuration to focus on in Chapter 5 and constructing a scenario space describing its possible developments in the future in Chapter 7 this chapter describes the modelling process and presents initial results. An exploration of the scenario space will be discussed in the following chapter. The modelling process follows the steps described in the Methodology chapter 3. The first step is to mimic the cluster's operation in a model, this step is presented in Section 8.1. Once the model is complete and running properly a validation will be done based on the electricity load data from the tank terminals, this is presented in Section 8.2. A complete and validated model is then used to perform simulations of the different scenarios. The construction of the simulation model and its output is described in Section 8.3. The assumptions made to support the construction of the model can be found in Appendix F. The analysis of the results will be discussed in the next chapter.

8.1. Modelling

In the design and execution of the electricity system model it is important to keep the goal in mind for which it is used. The ultimate goal of the research is to analyse future developments of the cluster's operation and identify drivers for change. The foundation for this analysis will thus be a model of its operation. As the focus of the research is to control electricity demand amidst a grid congested area the electricity flows following from the cluster's activities will be modelled.

8.1.1. Model description

A model for the electricity system can be derived from the energy hub model method from Geidl et al. [50]. Here inputs must equal loads times conversion parameters and efficiency constants. The load is described by the electricity demand of the components present in the cluster, each with their own consumption profile. Some simplifications can be made to Geidl et al. their approach due to the scope of the system that is modelled. Since only the electricity flows are considered there are no conversion steps. Moreover, efficiency losses of individual equipment will be accounted for in the description of every component's electricity demand. Since the companies in the cluster are assumed to be near each other the transmission losses can be assumed negligible. This means that the energy hub model by Geidl et al. can be simplified to input = output.

Current operation

Finding the solution to this equation starts by finding out what the electricity consumption of the cluster is. In order to generate a load profile of the entire cluster the load profiles of the individual companies can be generated. These load profiles are the sum of the components requiring electricity at the company's site. Following the data acquisition in Chapter 5, the cluster that will be modelled consists of four tank storage terminals. Research into the operation of the cluster is done through interviews with the terminal operators, additionally desk research is conducted [38, 141, 57, 182, 174, 108, 178]. This research is supplemented by interviews with sector experts at the Port of Rotterdam. From the study on tank terminal components a list can be made of components that make up a terminal's electricity load. This list was presented previously in Table 5.9.

Future additions
The model that is built to evaluate future scenarios on their electricity load will need to be able to calculate the load as a result of new assets that are placed on site. Technological innovations create new technologies that can be implemented at terminal sites. E-boilers, that were already mentioned in Chapter 5, could provide the heat demand from the terminal in the future. Generators, batteries, wind turbines and solar PV could all be installed in the near future as these technologies are already used for similar applications. In addition, companies throughout the Netherlands are electrifying their vehicle fleet. If terminals would have the capacity, they might do the same. Moreover, the first electric trucks are currently in operation [1]. These numbers are projected to increase significantly towards 2035 under AFIR legislation. AFIR enforces the development of charging infrastructure throughout Europe and will ban sales of new conventionally driven trucks from 2035 onwards [51].

A first outlook on future additions to the cluster's operation was discussed in Section 5.5. Even more innovations are projected to transform a tank storage terminal's operation in the near future, such as tank and pipe tracing or heat pumps. Moreover, the conditions in which products need to be stored might change if Europe switches to alternative fuels such as ammonia or hydrogen. These alterations will however not be accounted for by introducing new components in the electricity system model. For the case of tracing and heat pumps the transformation focuses on switching heat generation from fossil fuels to electricity. The component model for the e-boiler is built based on the estimated heat demand of the terminal and will therefore be similar irrespective of the specific technology that supplies this heat. Similar to the heat demand, no new components are modelled for a switch to alternative types of products. Alternative fuels often are stored at subzero temperatures, where conventional fossil fuels regularly need to be heated in order to maintain desired material properties. Mineral oil and crude oil are stored at ambient temperature or slightly higher (50 °C for crude oil), while ammonia is stored at -30 °C and hydrogen even at cryogenic temperatures of -253 °C. Nevertheless, no additional components are modelled for the transition to alternative fuels. Partly, this is because little information could be found on operational characteristics of tanks storing alternative fuels. Partly, no new model scripts are designed because the major changes associated with the storage of new products are capital investments that are not reflected in the model. The operational differences will largely result in an increase in pump usage or tank cooling. This variance is already incorporated in the model by the uncertainty ranges of current terminal components. In a way, a scenario where the amount of VRU's increases on site can also correspond to an intensified storage procedure. It is assumed and verified that power demands do not increase beyond projected growth ranges. For the components where this would be the case; e-boilers, EV charging and truck charging, additional components are modelled. For the case shore power is installed the power rating corresponding to the berth of vessels increases significantly.

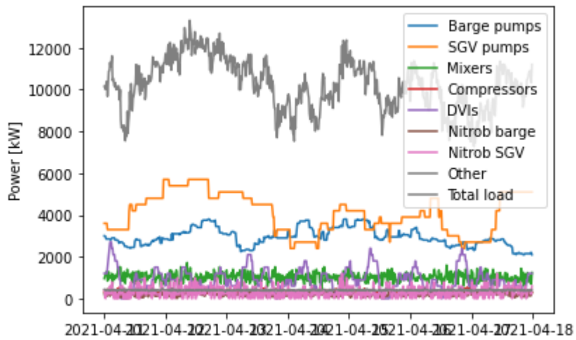
The other future additions to the asset mix mentioned in Section 5.5 are fuel cells and electrolysers. These technologies do however not naturally fit into the core business of a tank terminal. Little knowledge was acquired on the potential adoption of these technologies by tank terminals in the future. For this reason, both technologies are not included in the model of the energy hub.

8.1.2. Electricity load model
Before a load profile can be calculated the load profile for every component must be constructed. In order to do so the power rating and operating hours for every component must be expressed. Table 8.1 below shows these characteristics for all discussed components. Motivations for the values presented in the table are discussed in Appendix F as well as the sources on which the values are based.

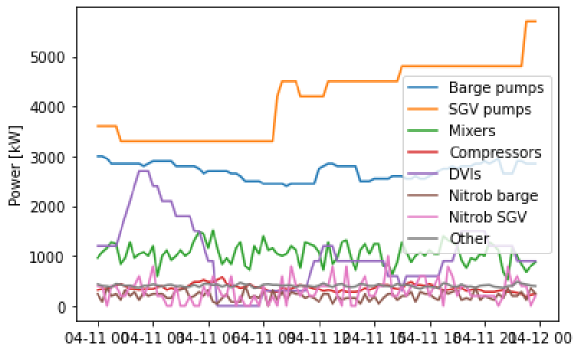
With the power ratings and operational characteristics of all components established, the load profiles of the components can be calculated. Calculations are done in Python using Spyder as IDE. This calculation consists of the generation of an operating schedule for each component and a power calculation. The generated schedule states the operating hours of a component for a scenario, the power calculation then uses this schedule in combination with the power rating of the component to calculate its power demand. When adding the power demand of all components for every timestep the load profile of a terminal can be calculated. The code used to calculate the load profiles of the individual components as well as the aggregated profile can be found in Appendix H. Figure 8.1 shows the individual component loads for components currently in use on a single day as well as the aggregated load for a single week.

Table 8.1: Tank terminal component specifications

Component	Power rating [kW]	Operating hours
Loading pumps barge	50	During barge berth
Loading pumps SGV	300	During SGV berth
Tank mixers	40	32 hours per month
VRU	300	25% of the time
Nitrogen blanketing barge	40	During 1/6 of barge berths
Nitrogen blanketing SGV	200	During 1/6 of SGV berths
Compressors	20	30% of the time
Office	83 kWh/m^2	Entire day
EV charging	7	8 hours every weekday
Truck charging	400	1/2 hour, 5 times a day
E-boiler	20,000	Seasonal variation, 50% on average



(a) Profiles of components and aggregated load

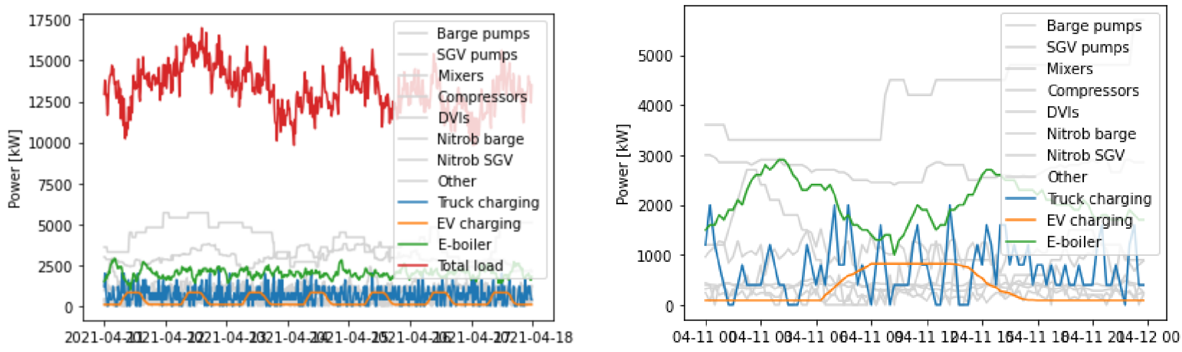


(b) Component loads during a single day

Figure 8.1: Load profiles for a week in April

The load profile shows that the loading pumps are the main contributors to the electricity demand. Both interviews with terminal operators as well as reports [108, 178] confirmed this as well. As mentioned in Table 8.1 the use of loading pumps is determined by the berthing schedule of vessels at the terminal. In the face of grid congestion industrial demand side response (DSR) is of great value. Since pumps demand a significant share of the terminal's load, flexible deployment could help mitigate peak consumption. Unfortunately, terminal operators do not influence the schedule of ship berths, as these are purely market driven (personal communication, 2023). A terminal can nevertheless influence the power at which loading pumps operate. Though, at times this might still be influenced by the vessel's schedule. The other components all operate based on fixed patterns, except for the tank mixers. Some of the mixers can supply load shifting where they can operate at different hours in order to reduce consumption peaks. From Figure 8.1b it can be seen that a certain base load is required due to product demands (e.g. product must be loaded and it needs to be mixed to enable product handling). Since only minimal flexibility can be achieved at uncertain times it is concluded that a tank terminal has no flex capacity on site with the current asset mix. This could change however if new components are added to the terminal's operation.

Figure 8.2 shows the load profile of both a week and a day when extra components are added, including a 4 MW e-boiler, some EV chargers for each terminals and truck charging. For the EV's it is assumed that cars can slowly charge throughout the entire work shift. For truck charging only a few chargers are installed, which provide 400 kW fast-charging to trucks while (un)loading. The power ratings assumed in this simulation are not sized for full electrification but rather show the electricity demands for early electrification efforts. For example the heating demand of the entire energy hub might amount to a few tens of MW, while 4 MW is chosen here. These assumptions are chosen to illustrate the significant increase in electricity demand that is already needed for partial electrification projects. Further assumptions can be found in Appendix F.



(a) Profiles of all components and aggregated load

(b) All component loads during a single day

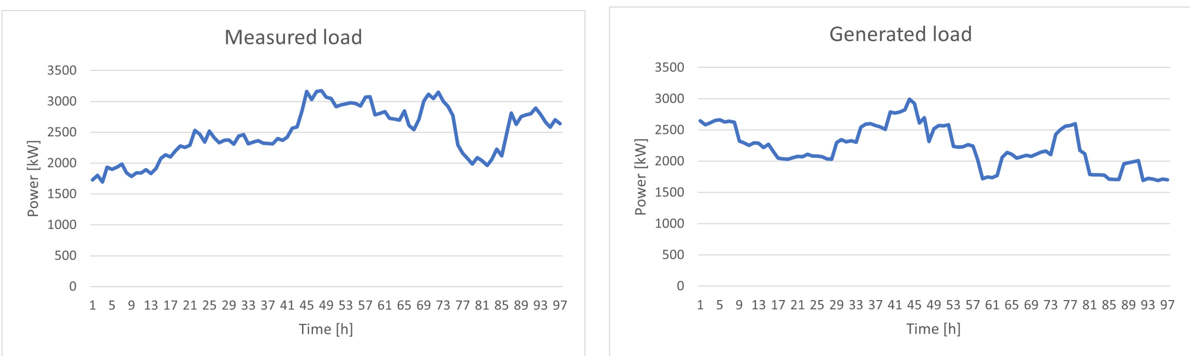
Figure 8.2: Load profiles for conventional and new components for a week in April

In Figure 8.2 the profile of EV charging can be recognised by its typical form. Throughout the workday cars of all personnel are charged, at night the personnel necessary to keep the terminal in operation are the only ones that charge their car. For trucks a more volatile profile is observed as this is dependent on the unpredictable arrival of trucks. For the e-boiler a capacity varying around 2 MW is observed for the month of April. During winter the average load will be higher. When comparing Figure 8.2a to Figure 8.1a notice that a higher peak demand occurs, as a result of additional installed components.

8.2. Validation

The component characteristics are mostly based on characteristics described in reports [38, 108, 178, 57, 182]. The profiles resulting from the exercision have been improved based on knowledge from industry experts at the Port of Rotterdam as well as data analysis. In order to improve and validate the generated load profiles the data obtained from tank terminals, which is elaborately discussed in Chapter 6, is used. A short overview of this process is provided here, for a more elaborate analysis refer to Appendix D.

The aim is to generate a load profile that accurately describes the terminal load. Starting from the profile that has been constructed based on characteristics described in the report, comparisons are made to the measured load data. Operating hours in the load model have been adjusted slightly to more closely align with the pattern of the measured data, while ensuring that the total annual energy consumption remains unchanged. Furthermore, an 'other' component is installed with a random operation distribution to account for observed load fluctuations in the measured data. In Figure 8.3 the measured load data and the constructed load profile for one of the terminals can be compared.



(a) Random weak in measured load data

(b) Random week in generated load profile

Figure 8.3: Load profiles for measured and generated data for a single terminal

The figures allow for a visual validation of the generated load profile; both profiles operate within the same limits and variance in power demand is comparable. An extension of this validation is done on, for example standard deviation, and can be found in Appendix D. While the results show the load

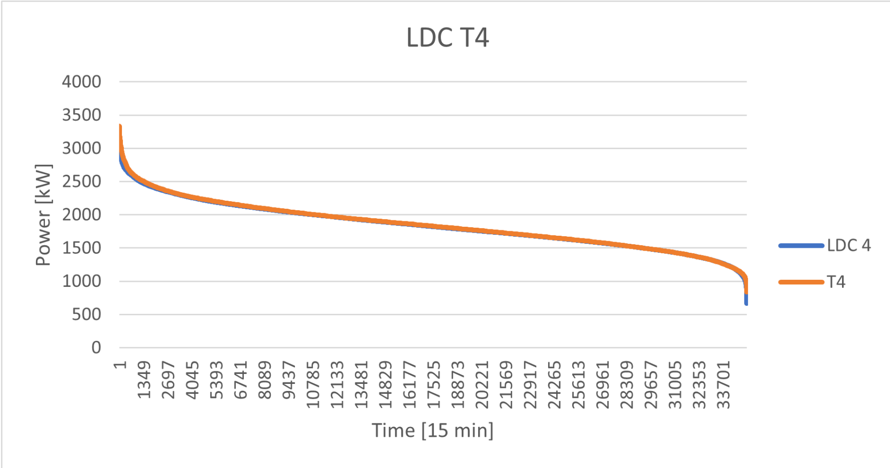


Figure 8.4: Comparison of measured and generated load profile for one of the tank terminals

profiles are fairly representative it is important to validate whether the generated profile operates at similar power levels throughout the year. For this validation a load duration curve (LDC) can be used. An LDC is a curve where a load profile is presented in order of maximum to minimum load, rather than in chronological order. An LDC thus shows how many hours per year the system requires a certain load. As the focus of the model will be the overload of the system it is important to generate a profile that has similar maximum load hours. Again, operating hours and power ratings are adjusted slightly to better resemble the LDC of the measured load data. A comparison of the measured and generated LDC after tuning for a single terminal are shown in Figure 8.4.

The figure shows two similar curves indicating that the generated load profile is an accurate representation of the load demand of a terminal. A similar process is executed for the other terminals. Details on this process can be found in Appendix D. These load profiles act as a first validation for the operational characteristics of the electricity load of the terminal components. In addition to the validation based on the measured data, terminal operators are approached to give feedback on the chosen power ratings and operating hours. The majority of values were confirmed, for some components minor adjustments were made. After making the final adjustments the electricity system model can be used to execute scenario simulations.

8.3. Simulation

The electricity load model serves as foundation for the eventual model that will be used to simulate scenarios using the EMA workbench [83]. The goal of the simulation model is to calculate the maximum overload that occurs for the terminal over a year. All 35,040 datapoints should be calculated for every scenario, which is often a size of 8000 experiments. However, since this requires significant computational effort, it is chosen not to calculate all datapoints. Instead, the first 672 datapoints are modelled which describe the first week of the year. This amount accounts for the minimal period in which some components operate; SGV's can lay berth for half a week. The only component with seasonal characteristics is the e-boiler. Since it shows the highest loads during winter, the first week of the year gives a good representation of the overloads of the system.

The electricity load model is split up so that the operating schedules of the components are generated at the start of a run, the power calculations are part of the simulation model. The simulation model is built according to the method suggested in the documentation of the EMA workbench; a function definition is used to describe the simulation model. Power calculations in the model make use of variables, relating to power ratings and amount of components installed on site. These variables are assigned outside of the simulation model. Following the EMA method all variables that correspond to levers and uncertainties are given a range of values they can assume within the model to account for different scenarios and potential outcomes. Furthermore, constants might be assigned for certain storylines that are simulated. These constants correspond to values of parameters for which the storyline wants to evaluate the effect on other parameters within the system. The simulation model uses modules from the EMA workbench to pick values out of the uncertainty and lever variable ranges, together with the model constants these form the load inputs to the model.

In addition to the power calculations for every scenario there are electricity inputs for every scenario. These consist of the grid connection supplemented by possible system solutions that were found to be beneficial according to Chapter 5. A connection with a nearby CHP-system or the installation of a battery are examples of additional electricity inputs. Whether or not a battery is installed, or a connection is made to the CHP-system, and at which capacity, is chosen by a module from the EMA workbench for every scenario. Since the simulations calculate the overload for each scenario, the outcome of the model is the remainder of the electricity input capacity subtracted by the maximum load for every scenario. The result of a simulation run is then a set of overloads for all scenarios that are simulated. Ideally, all scenarios that could develop within the specified ranges are calculated. However, due to the vast amount of variables and values they can assume this would result in an immensely large amount of scenarios to run. Instead, a sample of the complete scenario space is taken using Latin hypercube sampling which is the default sampling method used by the simulation module in the EMA workbench. A standard sample size of 8000 is chosen, which corresponds to 20 different sets of levers and 400 different sets of uncertainty parameters. For 672 datapoints a single simulation run took about 15 minutes. These sizes are chosen as the input dimensions consist of two levers and 41 uncertainty parameters. For both types of parameters a factor 10 is used to generate a sample [97]. Latin hypercube sampling is a statistical method for data sampling that generates near-random samples. If a sufficiently big sample is generated Latin hypercube sampling generates an evenly distributed sample. This is ideal for exploratory modelling as it allows for the exploration of the entire scenario space. The outcome of a simulation model run results in an overload calculation for the specified amount of experiments.

A scenario can be seen as a future state of the system. The model simulates scenarios for single future moments in time. To compare different future pathways, different storylines can be simulated where assumptions are made on certain parameters. The process of creating storylines to evaluate future pathways is described in Chapter 9. The exact code used for the simulation model can be found in Appendix H. The electricity load model formed the basis for the simulation model. Both models are built using Python and Spyder as IDE. The simulation model is run using the EMA workbench on a PC with 2.7 GHz Intel Core i7, 8GB RAM.

9

Robust adaptive strategy development

Now that a successful run is completed simulating 8000 experiments, the outcomes can be evaluated. The goal of this evaluation is to develop a robust strategy for the modelled energy hub. The first step of the evaluation is an exploration of the scenario space, based on the outcome sample. This will be described in Section 9.1. This exploration will be the basis for the draft of desirable future pathways, for which the process will be described in Section 9.2. In an iterative process these desirable pathways will lead to a robust adaptive strategy for stakeholders of the energy hub. This process is described in Section 9.3.

9.1. Exploration of scenario space

The simulation model has run 8000 iterations. The total number of simulations that are calculated consists of the amount of different sets of lever parameters that are used as input and the amount of different sets of uncertainty parameters. As explained in Section 8.3, levers correspond to the internal factors listed in the scenario design phase, uncertainties correspond to the external factors. When initialising a simulation run the amount of different sets of lever and uncertainty values that are chosen are described as the amount of policies and scenarios. If the simulation run is initialised with 10 policies and 10 scenarios, 10 near-random sets of levers and 10 near-random sets of uncertainty parameters are chosen and simulated. The outcome of such a run would be 10*10=100 experiments, where experiments is used to indicate the amount of individual scenarios that are run. In order to generate a representative sample, the amount of experiments should be as large as possible [184]. For the final simulation of the model a run was conducted with 8000 experiments. Consisting of 20 scenarios and 400 policies. The evaluation on the simulation results is done through feature scoring and with the help of PRIM-boxes, analysis tools provided by the EMA workbench. A sensitivity analysis on the outcomes is provided in Appendix G.

9.1.1. Feature scoring

The first step in the evaluation of the outcomes is an analysis on the simulation results using feature scoring. Feature scoring is a methodology for identifying which model inputs have the greatest relationship to the outputs [83]. The relationship is not necessarily linear, but can be any arbitrary linear or non-linear relationship. The feature scoring method in the EMA workbench uses the chi-square test between each non-negative feature and the target vector. The test measures dependence between the variables and the target value. The feature scoring for the relationship between the input variables and both the maximum load and overload is shown in Figure 9.1.

In total 43 variables are assigned in the model. Due to this large amount it is hard to distinguish the individual results. It is nevertheless not necessary to evaluate all parameters. The feature scoring shows the relative influence of the various uncertainty parameters on model outcomes. Parameters with a higher influence are indicated by a yellow, green or light blue bar depending on their score. The variable highlighted in yellow near the bottom for 'P_max_load' represents the variable related to the installation of shore power for SGV's in the different scenarios. Shore power requires a vast amount

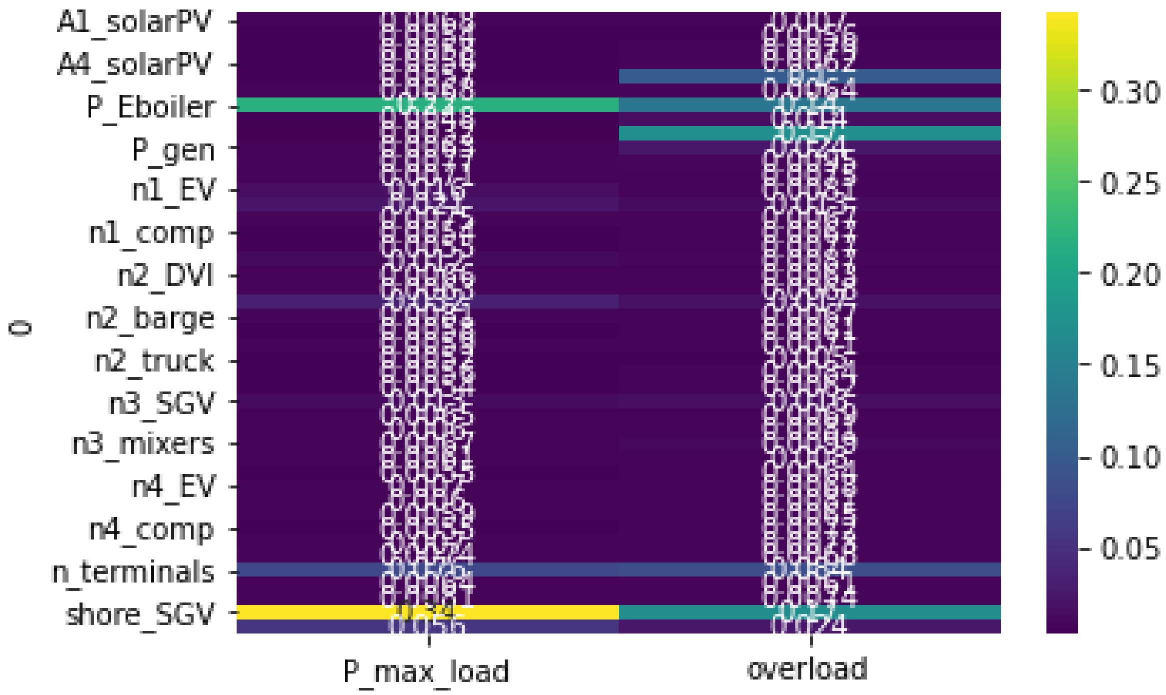


Figure 9.1: Result of feature scoring for both the maximum cluster load and overload in relation to all the input variables

of power, 2600 kW per SGV. The high power demand multiplied by the amount of SGV's mooring at the quays and jetties results in a higher load than any other modelled component, the score is thus as expected. Similarly, the operation of an e-boiler requires a large amount of power, up to 20,000 kW. The amount of terminals included in the energy hub also has quite a significant influence on the electricity load of the energy hub, indicated by its light blue colour. In the second column the influence of variables on the energy hub's overload is shown. Similarly to the maximum load, shore power for SGV's, the power required for an e-boiler and the amount of terminals are of greater influence on the overload. However, two groups of variables are highlighted as well that were not highlighted for the maximum load. This is because the variables, CHP-system connection and expansion of the grid connection, do not contribute to a high system load but rather cause overloads in scenarios where they shine in absence.

Table 9.1: Top and bottom 10 feature scores of the simulation run for 'overload'

Nr	Parameter	Score	Nr	Parameter	Score
1	P_elec	0.1704	34	n4_barge	0.0065
2	shore_SGV	0.1669	35	n4_DVI	0.0064
3	P_Eboiler	0.1356	36	P_DVI	0.0064
4	P_CHP	0.1009	37	n2_DVI	0.0063
5	n_terminals	0.0346	38	A4_solarPV	0.0062
6	P_gen	0.0238	39	n3_EV	0.0062
7	shore_barge	0.0236	40	n_wind	0.0061
8	n2_SGV	0.0167	41	n2_comp	0.0061
9	n3_SGV	0.0160	42	A2_solarPV	0.0056
10	P_bat	0.0139	43	n2_truck	0.0050

In Table 9.1 the top 10 and bottom 10 variables influencing overload are shown. Variables concerning the installation of shore power and the expansion of the grid connection top the table, followed by the installation of an e-boiler and a possible connection to a nearby electricity generation unit[1]. All the

[1]Model parameter 'P_CHP' refers to the possible integration with an electricity generation unit as described in Chapter 5

way at the bottom is the amount of truck charging points at terminal two. Since no variable regarding truck charging for any of the other terminals is mentioned in the bottom 10, this notion might be due to the specific sample used for this feature scoring. For other variables like solar PV or VRU[2] multiple variables are mentioned. Clear is that renewable energy systems will not be of great value in reducing overloads for the modelled energy hub.

9.1.2. PRIM-boxes

Chapter 2 already touched on the motivation for adopting an exploratory modelling approach. As the name suggests it allows for an exploration of the model outcomes. The model used in this research is capable of a more elaborate analysis than specifying which factors are most influential to the overload. In the end, this is directly related to the load associated with the modelled components. As opposed to a search for the ’right’ answer in other forms of modelling, such as predictive, exploratory modelling enables the researcher to review the entirety of the solution space. When designing a system within a changing environment there might not be a right answer to what *will* happen and subsequently what the best solution is. As such, it is interesting to examine what *could* happen in a range of scenarios and subsequently evaluate what this means for the design process.

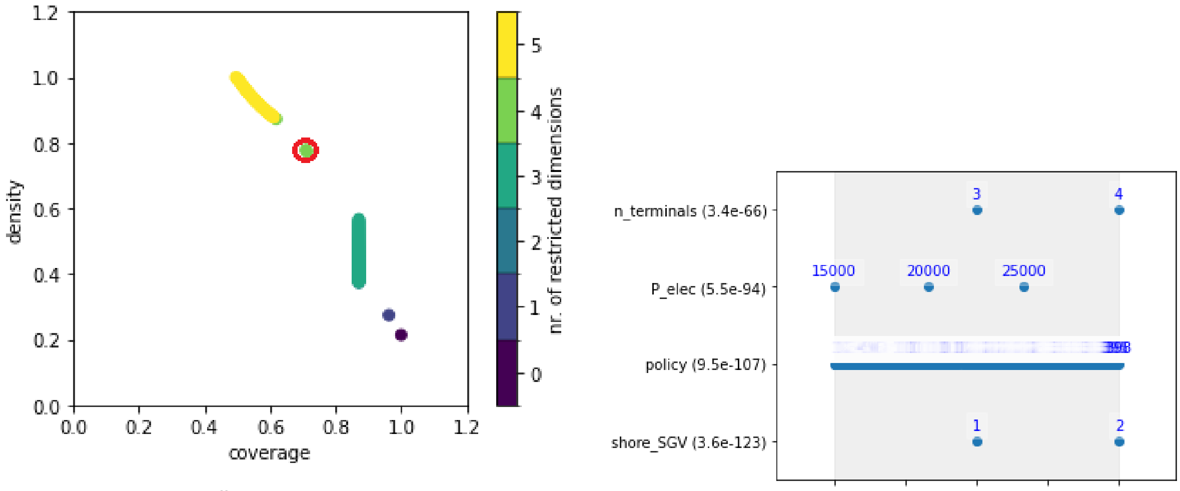
The exploration of the scenario space is facilitated by the PRIM-boxes that can be calculated using the modules provided by the EMA workbench. Similarly to feature scoring, PRIM calculates the influence of uncertain variables on an outcome. What makes PRIM particularly useful is that this relation can be researched for all possible outcomes, rather than for overloads as a whole. Thus, PRIM allows for an exploration through the scenario space. The Patient Rule Induction Method (PRIM) is a scenario discovery algorithm that operates on an existing set of data with model inputs as well as outputs. That means that a set of experiments has already been run previously, PRIM then uses the combination of inputs and outputs to perform analyses. When generating a PRIM-box a certain outcome of interest is specified out of the complete set of outcomes. What PRIM then does is identify subspaces that have a high concentration of experiments of interest. Every subspace corresponds to a set of intervals for some of the uncertain input variables that jointly characterise the subspace [156]. The PRIM-box thus describes what intervals for uncertain variables are influential to a certain outcome. The storyline described by the PRIM-box can be seen as a prediction of variables that lead to a certain outcome. After a PRIM-box is generated, another search is conducted to find a PRIM-box in the remaining data. After all PRIM-boxes are found, a dimension is restricted and the search is continued. The restricted dimension corresponds to the most influential variable. This iterative method of finding PRIM-boxes is called the ’peeling trajectory’ by PRIM’s developers [88].

Every PRIM-box is scored on density, coverage and interpretability. Density represents the fraction of relevant points within the box, relative to the total number of points in the box, and thus indicates the strength of the prediction. Coverage represents the fraction of relevant points within the box, relative to the total number of relevant points in the database, and thus indicates the relevance of the prediction. Interpretability is quantified by the number of boxes in a box set and the maximum number of restricted dimensions in any box. This metric is used to suggest the ease with which a box can be communicated and understood by decision-makers, but is highly subjective. A lower number of boxes and restricted dimensions helps the interpretability of a solution, too little restricted dimensions may not produce tangible actions however. Interpretability subsequently has no specific target value, though three or four restricted dimensions are preferred. Density, coverage and interpretability are negatively correlated where improving one of the metrics comes at the expensive of another [88]. The documentation for the EMA workbench specifies a threshold-value for density, ≥ 0.8 [83].

The PRIM-package used can be employed interactively to generate boxes that are most useful for the decision-making process. First, an outcome of interest is specified, in this research an overload of > 10,000 kW might be chosen. PRIM-boxes are then generated in case a PRIM-box exists with a density ≥ 0.8. The user then specifies which PRIM-box to analyse based on the desired density and coverage. In 9.2a an example of a plot showing density, coverage and interpretability is shown. The tradeoff between all three metrics becomes clear as an increase in one results in a lower score for the others. A score of 1 for both density and coverage would mean a perfect prediction for all outcomes of interest. As this is never the case a PRIM-box is chosen that is located the most upper-right. A maximum

[2]VRU translates to DVI in Dutch

score of both coverage and density is desired, as well as a low amount of restricted dimensions. On the right-hand side of the figure the legend for number of restricted dimensions is presented. The picture illustrates this is negatively correlated to density and positively correlated to coverage, as a lower amount of restricted dimensions indicates a higher interpretability.



(a) Plot showing tradeoff between metrics, chosen PRIM-box is indicated by a red circle

(b) Intervals for uncertain parameters for chosen box: Box 44

Figure 9.2: Density, coverage and interpretability for generated PRIM-boxes

Box 44 is chosen from the PRIM-boxes displayed in Figure 9.2a as it is regarded as the optimal tradeoff between density, coverage and interpretability. The details in Figure 9.2b show the intervals for the uncertain parameters that have a strong relation to the outcome of interest. So, the PRIM-box in Figure 9.2 tells us that an overload greater than 10,000 kW for the specified configurations is likely caused by a combination of the following factors; No company withdraws from the energy hub, no physical expansion of the grid connection and shore power is realised for SGV's. The policy parameter is not a specified variable, but the set of levers chosen for each scenario. Its inclusion in the PRIM-box happens on some occasions due to the way the coverage and density are calculated in the PRIM-package. For an elaboration on the parameters and the scenario's that correspond to them please refer to Appendix E.

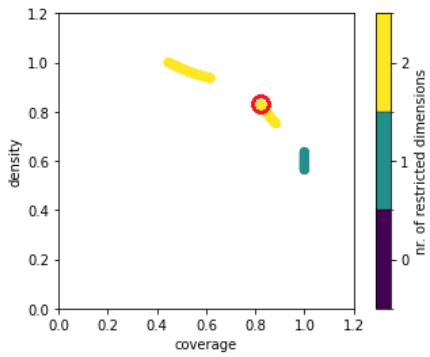
9.2. Future pathways

The aim of this research phase is to design desirable future pathways that are robust and are able to adapt to a changing environment. The EMA approach is used to find drivers for certain future pathways. Drivers leading to undesirable pathways can be avoided while drivers leading to desirable future pathways can be embraced. First, drivers that lead the system to its limits are explored. With a better understanding of the system and its behaviour in the scenario space storylines can be tested in the model. Decision-makers from the energy hub as well as the Port of Rotterdam can plot future goals or beliefs for certain developments in the model, EMA can then be used to evaluate how the system performs under certain circumstances.

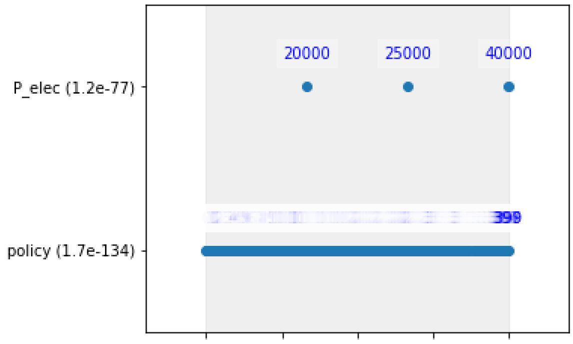
9.2.1. System limits

The first outcome of interest is the set of experiments that do not lead the system into overload. For this test the outcome of interest is set to zero. The results are displayed in Figure 9.3. Figure 9.3b shows that the single most influential parameter is the capacity of the grid connection. In the situation the grid connection is contractually or physically expanded, 71% of cases will not reach an overload state. The grid capacity of 20,000 kW corresponds to a cluster that consists of two or three terminals, 25,000 kW corresponds to the situations where the cluster consists of four terminals.

Equally interesting are the rest of the cases where the system does reach an overload state at some point throughout the year. For this outcome of interest the results are shown in Figure 9.4. Again, the capacity of the grid connection is the main influential factor to overload. Interestingly, this interval also



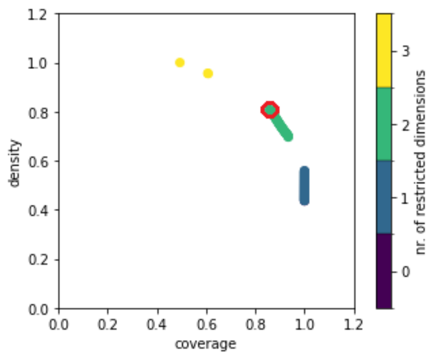
(a) Plot showing tradeoff between metrics, chosen PRIM-box is indicated by a red circle



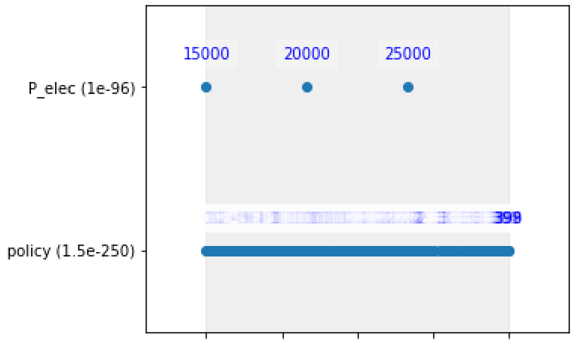
(b) Details of chosen box: Box 103

Figure 9.3: PRIM-boxes for overloads = 0

includes the 20,000/25,000 capacity value for the grid connection. This might be a result of the fact that 'P_{elec}' is regarded as the most influential parameter, but for coverage to be sufficiently high the extra value is included.



(a) Plot showing tradeoff between metrics, chosen PRIM-box is indicated by a red circle



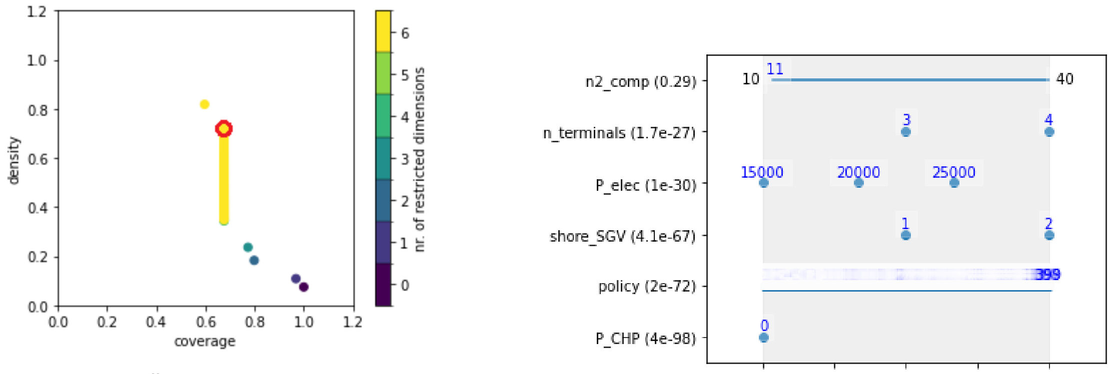
(b) Details of chosen box: Box 154

Figure 9.4: PRIM-boxes for overloads > 0

The capacity of the grid connection seems to be an important factor for the overload of the system. This is not surprising as Appendix F shows that the power capacity significantly increases when the grid is upgraded; the physical expansion of the grid connection results in the highest increase in capacity of all components. While these are valuable results for the decision-makers the set of scenarios to which they correspond is large, and therefore the results might be as expected. A finer approach is adopted when looking at outcomes that generate an overload > 20,000. This is the maximum overload for which the density requirement of $\geq$ 0.8 could still be met. This set of outcomes generates the worst-case scenarios. Results are presented in Figure 9.5. The insights from the previous run are extended by the addition of uncertainty intervals that make up the 'perfect storm' for the industrial energy hub. Again, the absence of a grid capacity upgrade to 40,000 kW is an influential factor to the outcome. From Figure 9.5b can be seen that severe overloads will be reached in many scenarios if next to the 40,000 kW grid capacity no connection is made to an electricity generation unit and SGV's have fully transitioned to shore power. Figure 9.5b also shows the interval for amount of compressors installed at terminal 2, however since almost the entirety of the uncertainty interval is included for the PRIM-box this parameter can be considered as less influential.

9.2.2. Storylines

The exploration of system limits has provided valuable insights, showing the significance of sufficient grid capacity. While it is now clear what should be avoided at all times, the circumstances under which proactive action can be taken are still unclear. Employing the EMA method enables the creation of



(a) Plot showing tradeoff between metrics, chosen PRIM-box is indicated by a red circle

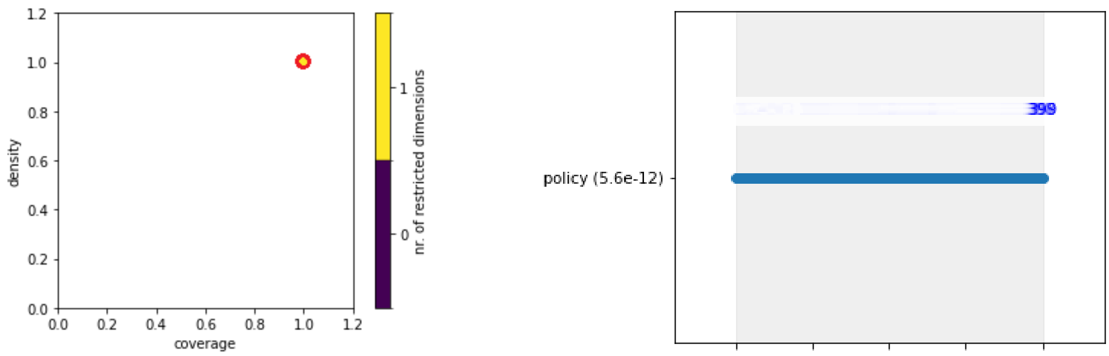
(b) Details of chosen box: Box 28

Figure 9.5: PRIM-boxes for overloads > 20,000

simulations that explore potential future scenarios, shedding light on the situations that may arise in this envisioned future. This approach facilitates the robust formulation of strategies, marking the first step towards strategic decision-making in this context. For different future pathways the system's performance will be tested; a future where electrification has not progressed further than its current state, a future in the early phase of electrification and a future pathway where the energy hub is electrified completely. For all pathways described in this subsection the tradeoffs between density, coverage and interpretability as well as the chosen PRIM-boxes are shown.

No electrification

The first future pathway serves as a reference. Here the situation is assessed where electrification has not progressed further than its current state. These scenarios represent the nearby future where for instance no e-boiler is installed yet and cars and trucks do not yet charge at the terminals. The first pathway that is simulated is also limited to the current grid capacity and has no connection to a nearby electricity generation unit. This relates to the current state of the energy hub, which has to wait for 'Loadproject Simonshaven' to complete before additional grid capacity can be issued. Possible increases in load demand come from the expansion of tank capacity or the construction of additional quays or jetties.



(a) Density, coverage and interpretability

(b) Details of chosen box: Box 28

Figure 9.6: PRIM-boxes for current state of electrification

If outcomes of interest was set to an overload greater than zero no boxes could be found with a density ≥ 0.8. When the outcomes of interest are set to zero the result is that the system remains within its limits for almost every scenario. The model shows the only exception is in the case the energy hub contains four terminals and all terminals see an increase in load demand due to, e.g. additional berth capacity, tank capacity, high VRU power rating. The conclusion can be drawn that the model suggests sufficient power capacity is available if no electrification plans are made. The results for this simulation are presented in 9.6 showing only little PRIM-boxes are found, due to the few outcomes of interest.

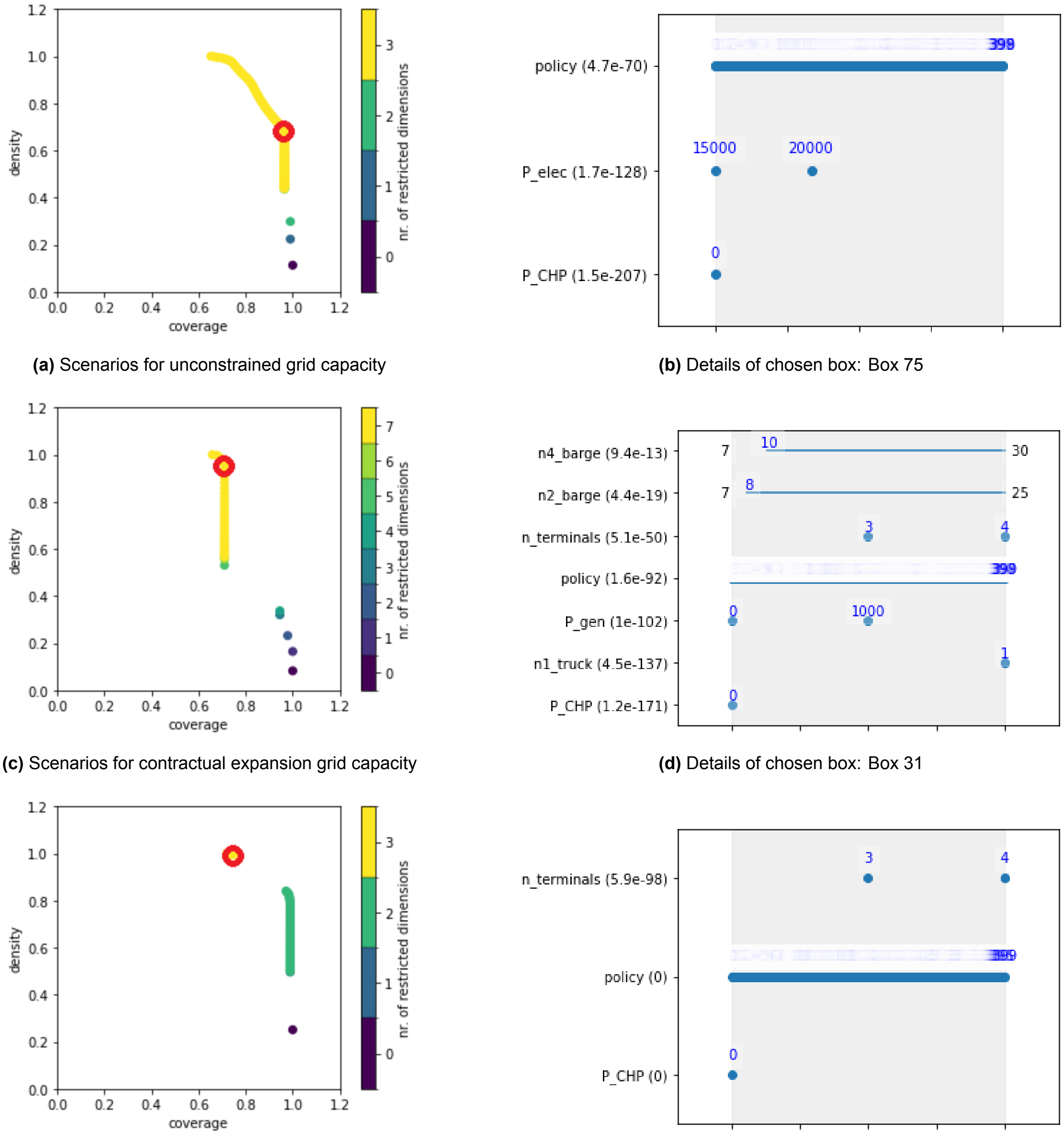
Early electrification
From the simulations on no electrification it seems the cluster would suffice with the currently installed grid capacity for nearly all future scenarios. Caution is advised for the expansion of high load assets, but still in most cases no overloads will occur. This is however just for the mix of components that are currently installed at the terminal sites. As the decarbonisation targets of 2030 loom ever closer companies in the HIC Rotterdam are urged to electrify processes that are currently fossil-based. In the coming years electrification will continue to transform the industry. It is not yet expected that installations in the range of tens of MW will be installed, partly because the power grid will not be ready. As of now, the installation of e-boilers is hindered as a result of the current state of the electricity grid. For the case of shore power for SGV's, it is not expected that these will be installed in the coming years as SGV's themselves are currently not fitted to be electrically powered. Examples where electrification might already be implemented are road vehicles. The electric vehicle is already matured and many companies throughout the Netherlands have already established a fully electric fleet. For heavy-duty vehicles the first orders are currently on the road. Therefore, in the early electrification pathway it is assumed that if terminals provide truck charging, this is still only for a limited amount of vehicles. Furthermore, the Port of Rotterdam is putting great effort into the adoption of shore power. Resulting in a lot of shore power berth options in the port area for barges already. In this pathway the assumption is made that terminals may choose to adopt shore power as well, ranging from no shore power to fully electric berthing. Three distinct scenariosets are tested. For the first the grid capacity is unconstrained and all scenarios regarding the grid capacity are included. For the second scenarioset the grid capacity has a maximum expansion of 5000 kW. For the third scenarioset the grid connection is limited to its current capacity. The results of the EMA simulations are presented in Figure 9.7.

The PRIM-box selected in the first scenarioset, shown in Figure 9.7b, states that overload is likely to occur in cases where the grid connection is not expanded and remains 15,000 or 20,000[3] and no integration is made with an electricity generation unit. The plot shows a high coverage score for the selected PRIM-box which indicates that most of the outcomes of interest are characterised by the uncertainty intervals described by the PRIM-box. The statement on the integration with an electricity generation unit is confirmed by the second and third scenarioset. In the results of the second scenarioset a relatively high number of dimensions are restricted. The conclusion that can be drawn from the PRIM-box of the second scenarioset is that in the situation where the amount of companies within the energy hub stays the same or increases, limited or no generator capacity is installed, limited truck charging is installed and no connection is made to an electricity generation unit, overloads are likely to occur. The PRIM-box has a high density score and thus represents an accurate prediction for the outcome of interest. Nevertheless, the high number of restricted dimensions illustrates the difficulty of pinpointing what factors are most influential, and therefore for decision-makers to decide on their approach.

The sets of scenarios ran to evaluate the system's performance for early stages of electrification highlight the need for a significant increase in grid capacity to facilitate this transition. In the scenarios where grid capacity is limited, the PRIM-boxes show that overloads are likely if no connection is made with an electricity generation unit and the amount of companies in the energy hub does not decrease. If electrification were to accelerate in the upcoming years already, before project 'Loadpocket Simonshaven' is commissioned, an urgent need for solutions would arise. These solutions will need to create large increases in power capacity to support these first electrification efforts.

Full electrification
While the need for severe capacity expansion already arises for early electrification efforts, the HIC Rotterdam will want to facilitate full electrification in the future as well. For the four scenariosets that are tested below some assumptions are made on the electrification route of the terminals. The Alternative Fuels Infrastructure Regulation (AFIR) by the EU states that by 2035 all cars will need to be emission-free, for trucks this is enforced in 2040 [51]. While there are alternative powertrains that are emission-free, the assumption is made that all vehicles visiting the terminals will be electric. Additionally, a significant part of a terminal's energy demand is related to its heat demand. While multiple decarbonisation routes exist, heat supplied by molecules is regarded to be too expensive. Green molecules are deemed to provide the chemical industry with feedstock instead of being burned for heat (personal communication, 2024).

[3]For a cluster with 2 or 3 terminals 15,000 kW is assumed. For a cluster with 4 terminals 20,000 kW is assumed



(a) Scenarios for unconstrained grid capacity

(b) Details of chosen box: Box 75

(c) Scenarios for contractual expansion grid capacity

(d) Details of chosen box: Box 31

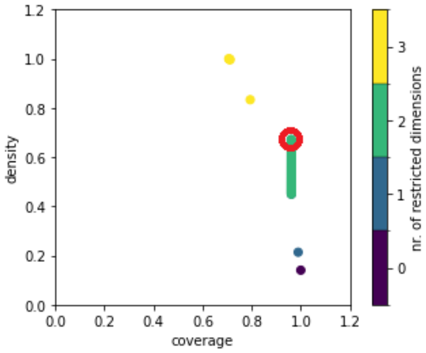
(e) Scenarios with current grid capacity

(f) Details of chosen box: Box 75

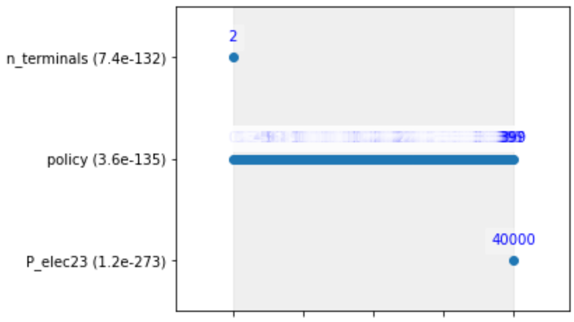
Figure 9.7: PRIM-boxes for early stages of electrification

The first scenarioset evaluates the situation where the terminals are all fully electrified and mitigation efforts such as grid capacity, CHP-system connection or the installation of a wind turbine are unconstrained. Since previous simulations indicated that the capacity of the grid connection is often the most influential factor to the overload of the system in the second scenarioset and subsequent scenariosets it is assumed that the grid expansion will be concluded by the time the energy hub is fully electrified. Evaluation of this scenario will give insight into the remaining efforts needed to complete the electrification plans. Here, it might be interesting to evaluate the amount of scenarios that lead to an overload in comparison to the ones that do not. This will give insight into the probability of successful electrification.

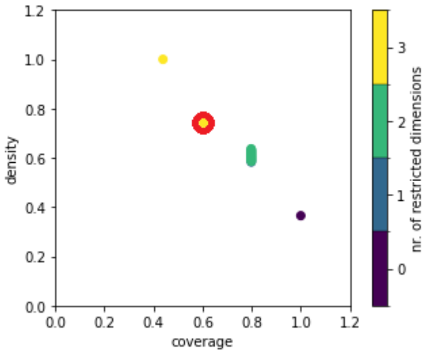
For a complete decarbonisation of the cluster's operation it is however not necessary for all processes to transition to electricity as energy carrier. For example for SGV's it is still unclear what the decarbonisation route will look like due to the large electricity and power volumes associated with its operation. The third scenarioset therefore looks at the situation where the operation of SGV's is unconstrained, meaning that some may choose to electrify while others might adopt alternative routes. The fourth looks at scenarios where both barges and SGV's decarbonise along various routes.



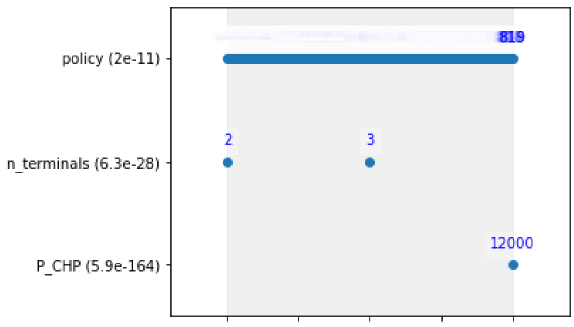
(a) Scenarios for unconstrained grid capacity



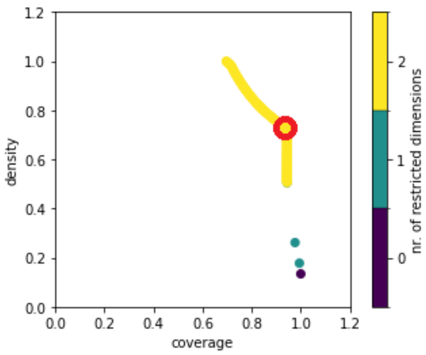
(b) Details of chosen box: Box 135



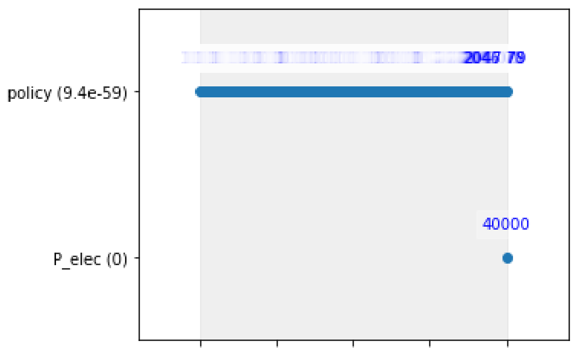
(c) Scenarios for expanded electricity grid



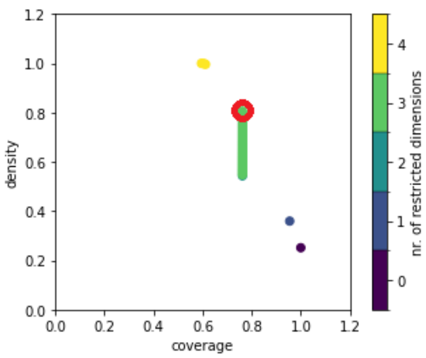
(d) Details of chosen box: Box 19



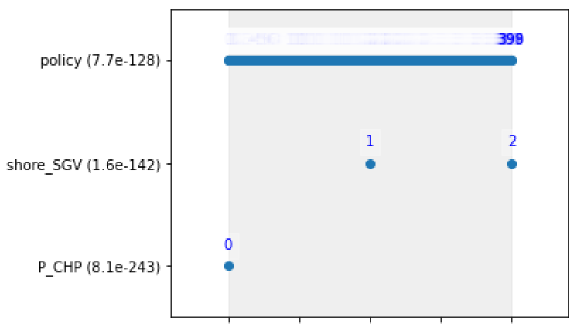
(e) Scenarios for alternative SGV decarbonisation



(f) Details of chosen box: Box 121



(g) Scenarios for undecided shore power route



(h) Details of chosen box: Box 48

Figure 9.8: PRIM-boxes for full electrification

The first PRIM-box indicates that a combination of only two terminals in the cluster and a grid capacity of 40,000 kW likely do not result in overload of the system. The high coverage of the PRIM-box shows that most of the subspaces that have no overload are characterised by these two variable values. The second scenarioset looks at the situation where the grid is expanded and is able to provide 40,000 kW electricity capacity to the terminal. The PRIM-box shows that again overloads occur less if only two or three companies are connected in the energy hub. Furthermore, the connection to an electricity generation unit is influential in preventing overloads, as was concluded for previous simulations as well. The simulation run also shows how many of the simulations did not result in overload. For the second scenarioset 2921 out of 8000 scenarios did not show overloads throughout the year. Meaning 63% of the simulated scenarios experienced overload at some point throughout the year. From this number can be concluded that significant efforts will need to be made to make sure that electrification can continue to progress.

While for the first two scenariosets it is assumed that all vessels will electrify in order to decarbonise, this will not necessarily be the case in the future. The third scenarioset looks at scenarios that do not show overload, while the fourth calculates PRIM-boxes that indicate uncertainty intervals for overload cases. Both show the importance of an interconnection with an electricity generation unit. Furthermore, the degree of electrification of SGV's influences the system's overload.

9.3. Robust adaptive strategy development

The results of both the feature scoring and PRIM-analyses show similar results. The installation of shore power or an e-boiler are highly correlated with overload occurring. Increased grid capacity and the integration with an electricity generation unit are important mitigation measures to facilitate these electrification plans and refrain from overloads happening. In the process of gathering results a robust adaptive strategy has developed. While the grid capacity is sufficient for the cluster's current operation and even so for the case companies in the cluster are looking to expand their operation, it quickly becomes insufficient when companies are starting to electrify their processes. A potential solution might be the installation of a battery system or a generatorset. While these systems might very well be a solution to a company's specific needs, the modelling results suggest they are less influential than alternative additions. The same holds for the implementation of solar PV or wind turbines. The model results indicate that the most impact is made through large-scale solutions. The expansion of the grid's capacity is a crucial part in the electrification process of the HIC Rotterdam. Still, even with a grid capacity of 40,000 kW only 2921 out of 8000 scenarios show no overload. To assist the grid a promising solution is the integration of an electricity generation unit. The high power ratings of units installed in the HIC Rotterdam can significantly boost a cluster's electricity capacity. For many of the electrification ambitions additional electricity capacity is needed. The integration with a nearby electricity generation unit can facilitate the cluster's electrification efforts if lead times for grid capacity are uncertain.

10 Discussion

This chapter serves as a critical examination of both the research findings and the methodologies employed throughout this research. This discussion aims to provide a holistic understanding of the study's contributions, limitations, and implications. First a discussion is presented on the findings from this research, then the methods applied are discussed and their limitations.

10.1. Research findings

On energy hub integration in general multiple remarks can be made, some of which are already mentioned throughout the report. Many factors might hinder the adoption as little experience is yet gained. Agreements on investments, interdependencies and legal frameworks are needed before energy systems can be interconnected. Fortunately, steps are being taken by multiple organisations to accelerate the adoption of energy hubs. The Netherlands Enterprice Agency (RVO in Dutch) is currently working on legal frameworks for a contractual connection between companies' grid connections. MOOI EIGEN develops a blueprint for an energy hub from conception to exploitation. Nevertheless, even with these tools in place the adoption of energy hubs throughout the Netherlands is not evident. Though an energy hub might provide benefits to some clusters, for an individual company concessions will need to be made as well. A company will inherently sacrifice some independence and is likely forced to make changes in its operation as well. Lastly, maybe the most important consideration is the possibility of adverse effects on grid load when grid operators are not involved in the creation of an energy hub.

The calculations performed by system operators in Chapter 4 regarding the load flows should be interpreted with caution. As described in the respective chapter, these calculations are based on historical load measurements combined with a coincidence factor. However, past load data does not necessarily reflect future consumption patterns, especially as industries are amidst an energy transition. The calculations made by the grid operators thus do not provide an accurate depiction of future load flows, as indicated in their reports. Furthermore, grid operators are forced to make predictions on load demands with limited knowledge of expected developments among their clients. Therefore, the calculated predictions from the grid operators should be interpreted as potential future scenarios, similarly to the scenarios outlined in this study, serving as a warning signal to stimulate decisive action.

The outcome of the cluster selection in Chapter 5 suggests increased reliance on fossil fuels through the CHP-systems, contradicting the principle of decarbonisation. However, leveraging flexible generation capacity facilitates the electrification of an emission-intensive industrial area. Over time, there is even potential for these fossil fuels to be replaced by e-fuels, ammonia or hydrogen, thereby enabling the transition to green flexible generation capacity. This presents a nuanced perspective on the apparent contradiction between short-term fossil fuel use and long-term decarbonisation goals. By strategically deploying flexible generation capacity, a pathway is manifested towards transitioning away from fossil fuels and achieving sustainability objectives in the future. This underscores the importance of considering both short-term practicalities and long-term sustainability goals in energy system planning and decision-making processes.

Due to limited knowledge of the characteristics of processes integral to the activities of the tank terminals, the elaborated scenarios described in Chapter 7 are constrained in their level of detail. Consequently, the simulation model lacks complexity and is not able to generate innovative insights. The conclusions drawn in Chapter 9 are unsurprising as it is obvious that installing high loads requires larger transmission capacity. A more elaborate model would enable the exploration of the scenario space in a finer resolution. This enhanced level of detail might provide insights into specific combinations of factors that result in interesting future pathways. Suggestions for refining the model are made in the next section. The outcomes of the model however do show the applicability of the method; the fact that the conclusions drawn from the simulation outcomes are unsurprising shows the model is able to support planning decisions for future energy systems. A finer model might help to gather insights that are not on the radar of decision-makers yet.

10.2. Applied methods

In addition to points of discussion for the research findings, certain aspects of the applied methods warrant careful consideration as well. For some of the research phases points of discussion are elucidated.

10.2.1. Cluster selection

The lists presented in Chapter 5 describe components of which an energy hub can consist. It is however hard to confirm if this list is exhaustive. Due to the open-ended nature of the search for components, it is challenging to assess what may be missing from the list. Particularly difficult is predicting the future development of the components listed and whether they may indeed offer potential in an energy hub context. Additionally, there are ”unknown unknowns” regarding components that may prove useful in the future but whose characteristics are currently unknown. However, since the angle adopted is to build an energy hub that can help mitigate current grid congestion, future additions can be omitted.

Limits on the exclusion criteria are that these are highly subjective. While the outcome yields a scalable solution, it has been demonstrated that establishing an energy hub is context-dependent. Several technologies that are currently filtered out might potentially offer flexibility in specific circumstances. However, there is no publicly available knowledge or expertise within the Port of Rotterdam to understand and incorporate this into the selection process further than has been done.

Discussing the outcomes of the data inquiry following the cluster selection, it would have been interesting to involve different types of businesses in the energy hub to explore potential synergies in this mixed operation. Unfortunately, there was no additional party ready to provide information or data. However, as evidenced throughout the project, an energy hub is highly dependent on its specific case. An energy hub integrating distinct companies looks different from one involving others. Therefore, even with the inclusion of a different type of business, it would have been challenging to devise scalable solutions. Continuing on the topic of data inquiry, it would have been beneficial to be in close contact with the data owner to fully understand how it was generated and what it does and does not describe. This would also have benefited the creation of the energy hub load model and subsequent simulation.

10.2.2. Sizing

The sizing of the generator and battery is somewhat arbitrary, caused by a lack of clarity on what would constitute an appropriate sizing. Without a comprehensive understanding of the specific energy demands, usage patterns, and potential fluctuations within the energy hub system, achieving an ideal sizing becomes increasingly difficult. This inconvenience continued for the sizing of the energy hub components where it proved to be difficult to build a sound configuration without expert knowledge on the operation of a terminal and its components. The correspondents did help in the validation of system parameters. These can be thus be assumed to be valid. Their specific operation, regarding power usage over the day is validated by reports on terminal’s operation for most of the components. The operation of components drawing the most power could be validated through this literature search. However, in practice this might still vary according to specific terminal operation. The outcomes of the load model can thus not be assumed to be representative for every tank storage terminal, rather it serves as an example of what the loads could look like.

10.2.3. Scenario design

Scrutinising the use of the EMA method for a horizon of more than 25 years raises questions on its applicability. This method, aimed at simulating 'all possible futures' to mitigate uncertainty, inherently faces limitations when applied to estimations made over such extended timeframes. Over a span of 25+ years, unforeseen factors that may not currently be within the realm of anticipation could significantly impact outcomes, thus challenging the notion of encompassing 'all possible futures.' While 'known unknowns' can be integrated into simulations, the influence of 'unknown unknowns' becomes increasingly pronounced over such extended horizons. When employing EMA to craft a robust strategy, it becomes imperative to describe the future as comprehensively as possible. However, the presence of 'unknown unknowns' perpetuates substantial uncertainty surrounding model outcomes. Thus, despite its broad scope, EMA may not fully address the depth of uncertainty inherent in long-term strategic planning.

For the quantification of parameters as part of the scenario design publicly available reports were used describing visions for the future. On some parameters tangible data could be found, e.g. a doubling of grid capacity following the commissioning of grid expansion 'Loadpocket Simonshaven'. For others it appeared rather difficult to find conclusive arguments. As the simulation model is intended to construct scenarios for a wide range of futures, it is forgiving of any impurities in the parametrisation. To follow this thought, for the parameters for which no tangible predictions could be found an attempt is made to adopt a wide range. Nevertheless, the outcomes of the scenario simulation should be interpreted with caution as they cannot be perceived as maximum or minimum limits to the cluster's operation.

10.2.4. Modelling

Addressing the validity of simulated outcomes poses similar challenges as for the establishment of scenario parameters. Validation could theoretically be achieved by comparing the simulated outcomes with predictions regarding the operation of the cluster in the future. However, seldom do extensive predictions exist and are often confidential if they do. Additionally, validation through expert input could have provided valuable support for the outcomes, but access to such expertise was limited. Attempts were made to outline future trajectories for the terminal cluster during workshops. However, the knowledge base of the participants proved to be too restricted for this purpose. Thus, despite efforts to validate the simulated outcomes through various means, limitations in data availability and expertise constrained the extent to which the realism of the outcomes could be assessed. The steps leading up to the simulations have been validated, which provides some substantiation to the validity of the simulation outcomes. Though caution is advised as errors might have slipped in the simulation process, leading to inapplicable or implausible outcomes.

Assuming the simulation model is capable of generating valid outcomes, several interesting additions to the results could be made. One is already mentioned and concerns the knowledge from terminal operators to generate a load profile using the exact characteristics from real components. A fairly similar profile is generated in this research as is described in Chapter 8, which is confirmed by the detailed analysis in Appendix D. However the detailed analysis also shows some difference in standard deviation and skewness between the measured and generated profiles. A more accurate profile would increase the credibility of the results, for specific cluster cases.

A finer model can also be created when more parameters are described in the model, as well as improving their link to a developing operation. Assumptions are made on the effects that internal and external factors can have on the cluster's operation. In reality however these effects might be even more interconnected than is assumed in this research. The increased storage of hydrogen, for example, could have implications on the use of certain assets, berthing schedules of vessels and even the asset mix present on the cluster. With a better understanding of the consequences of certain developments, more parameters can be added to the model, as well as interconnections made between parameters.

10.2.5. EMA

A limitation on the outcomes of the simulation model is that certain results had to be interpreted by the user. While the inherent aim of EMA is to provide insights which can then be interpreted and translated to concrete actions, the results from some of the simulation runs were unconvincing causing doubts about their credibility. An example is Figure 9.5b where almost the entire interval for amount of compressors installed is described as influential parameter, just as for the variable 'policy' which is not a specified variable but the set of chosen levers. This might have to do with the way density, coverage and interpretability are calculated but does not contribute to a clear storyline. The other variables presented as influential in all scenario simulations however are as expected and tell the story of overload development in the cluster.

A point of discussion on this outcome of interest can be made however. While overload is arguably the most valuable metric in the evaluation of an energy hub's performance in the face of congestion it might be argued that the potential of the EMA approach is not fully taken advantage of. The strength of EMA is that it is able to create insights into highly complex systems by utilising brute computational power. Storylines describing a desirable future pathway for one metric can be analysed on their effect on other metrics of performance of the system. When only a single model outcome is evaluated outcomes will be generated that are in most cases as expected beforehand. Nevertheless, EMA is a useful tool to simulate a near-random sample from a wide scenario space. Scrutinising the outcomes of a simulation for all plausible scenarios can provide valuable insights into the probability of certain futures.

Another aspect where the strength of the EMA approach is not fully taken advantage of is the possibility to generate scenarios that span multiple timesteps. When simulating scenarios it is possible to include multiple timesteps in order to evaluate development over time. Choices made in a timestep can then effect outcomes in later timesteps. By implementing this functionality EMA is able to give insights into the effect of certain choices, as some future outcomes might be restricted based on choices made at crossroads in the scenario. For the model used in this project no timesteps are included due to the adaptability of included parameters. For all parameters included in the system it can be argued that in five years time the value for the parameter has changed[1]. For example, while in one year the energy hub might expand through the inclusion of an additional company, the five years later the energy hub might include fewer members due to companies parting from the energy hub or dismantling their operation. Even grid capacity can be argued to be adaptable as grid operators and the regulatory body (ACM in Dutch) are discussing the introduction of a 'use it or lose it' policy to help in alleviating grid congestion. While the multi-step functionality is not employed in this research, the EMA approach is still valuable due to its ability to gain insights into the possible evolution of the system within the specified uncertainty intervals.

Furthermore, similarly to how the model can be refined, the analysis based on the simulated scenarios could be improved by a better understanding of the cluster's operation. In collaboration with companies in a cluster, specific storylines can be designed that can be evaluated using PRIM-boxes. PRIM allows for a detailed exploration of the scenario space. This does however require a finer model as well as a finer search area. If the model could be extended to describe future pathways in more detail the model could be used to gain specific insights. For example, an excellent application of the model would be to explore how the cluster would be affected if the proportion of hydrogen, ammonia, or other new products were to increase due to changes in the energy system. With insight into the specific components of the terminal, this could be traced back to adjustments in, for instance, pump usage or heat demand. Simulating future scenarios with a more refined model could yield valuable insights into potential bottlenecks arising from certain combinations of factors. Thus, while the current scenarios may lack granularity, leveraging the model to investigate these dynamics could enrich the understanding of the terminal cluster's resilience and adaptability in evolving energy landscapes. If the model can then also be extended to simulate over a time series, it poses a valuable tool to design robust adaptive strategies for energy system planning.

[1]This characteristic is evaluated on a period of five years, since this is assumed to be a timespan in which companies evolve

11 Conclusion

In this chapter the outcomes of the thesis project are concluded on. First, the answers to the five subquestions are presented, which together form the answer to the main research question. Following the conclusions drawn from this research, recommendations are made and suggestions for future work are offered. Lastly, a personal reflection on the research project is discussed.

11.1. Research questions

In Chapter 2 the outcome of the literature review is a knowledge gap in the academic discussion on future planning for energy hubs. To answer this knowledge gap a main research question is drafted. In order to find an answer sub-questions are derived. In this section, answers to the sub-questions are formulated after which the answer to the main research question is presented.

11.1.1. Sub-questions

1. What are the primary factors contributing to grid congestion in the HIC and how do these factors interact to create grid congestion?

Calculations on the load flows in the HIC Rotterdam show that a deficit in transmission capacity is foreseen for the period until 2027-2029, when project 'Loadpocket Simonshaven' is commissioned. The transmission capacity in addition with technical measures is sufficient to supply the required transmission capacity until the grid is expanded. However, there is no possibility for connection requests on the waiting list to be issued. These connection requests accumulate to 426 MW. This reality is disastrous for the business climate as companies are hindered in their expansion plans. Companies looking to establish new business in the port can not get a grid connection, forming an undesired barrier to entry. Additionally, while the HIC Rotterdam has a big role to play in reaching sustainability targets, these will be hard to meet if the energy transition is delayed due to grid congestion. Predictions on the future state of the grid are however difficult to model due to confidentiality surrounding the use of connection requests and investment strategies by the industry. The exact modelling outcomes presented in the congestion study should therefore be interpreted as a call for action rather than accurate predictions on the future state of the electricity grid.

2. What types of energy hub are applicable in the HIC Rotterdam?

An analysis on potential building blocks for an energy hub in the HIC Rotterdam showed that little scalable conversion components can be utilised to create flexibility in electricity supply. A single solution was found in electricity generation units present in the area. Mapping the found solution in the HIC Rotterdam resulted in more than 3634 MW of generation capacity that potentially can be employed to provide local flex capacity, within a congested area. In addition to this potential energy system integration solution, generatorsets and batteries can provide an industrial cluster with additional electricity capacity. From the data request following the cluster selection, four tank storage terminals were found to be willing to provide load data. An analysis on the electricity load data learned that load balancing can reduce peak power demand by 1748 kW. Adding a battery system to the cluster's electricity system can reduce the peak load even further, by 3448 kW in total.

3. What uncertain energy system developments might influence the integration of an industrial cluster into an energy hub within the HIC?

External and internal factors that might influence the operation and development of the cluster of terminals are described in Appendix E. Through desk research and two workshop sessions the list of factors has been compiled. Subsequently, the factors have been parametrised and parameters have been quantified.

4. How can the effects of an energy hub on changing energy use in a congested area be modelled?

The effects of energy hub integration and potential flexible solutions on a cluster's energy use can be modelled by a simulation model that calculates the maximum overload of the system in a range of scenarios. This simulation model is created through a number of steps. First, the electricity load of the cluster is generated by describing the behaviour of all system components and modelling each component's individual power demand. The sum of all components represents the electricity load of the energy hub. Through the use of EMA the system's future states can be simulated as well as the effect of energy hub solutions on the system's performance. The system loads act as behavioural relations in the simulation model. Uncertainty intervals are given from which EMA extracts inputs for the simulation model. The maximum overload in a year for each scenario is the metric of performance for the model.

5. What factors influence the success of the implementation of an energy hub in the HIC in an evolving energy landscape?

The influence of modelled parameters are evaluated through the use of feature scoring and a PRIM-analysis. The results of both the feature scoring and PRIM-analyses show similar results. The installation of shore power or an e-boiler are highly correlated with overload occurring. Expanding grid capacity and integrating with electricity generation units are important mitigation measures to facilitate these electrification plans and prevent overloads from happening. Three different storylines are evaluated on their performance and insights are gained into parameters influential to their outcome. The model shows that current grid capacity is sufficient for the cluster's current operation and even so for the case companies in the cluster are looking to expand their operation. If companies are looking to electrify their processes, grid capacity quickly becomes insufficient. The model results indicate that the most impact on overload prevention is made through the adoption of large-scale solutions; the expansion of the grid's capacity is a crucial part in the electrification process of the HIC Rotterdam, as well as the integration of an electricity generation unit.

11.1.2. Main research question

How can a robust adaptive strategy be developed for an energy hub that enables industrial activities within the congested HIC Rotterdam in a changing energy system?

The question can ultimately be answered by evaluating scenarios that showcase the potential development of an industrial cluster within the HIC Rotterdam. In order to find an answer to this question a research is conducted along successive steps. The first step is to gain insight into the congestion problem within the HIC. A cluster is then selected that can benefit from energy hub integration in the face of grid congestion. This system is then modelled, after which scenarios can be generated using EMA. Scenarios are evaluated through feature scoring and a PRIM-analysis. The modelled energy hub is located in the areas Europoort, Botlek or Pernis, and consists of four tank terminals. Scenarios evaluating its performance in various configurations show that a large-scale capacity increase is required to facilitate electrification of the cluster. A large increase in capacity can be realised by the integration of an electricity generation unit in the energy hub. However, the cluster's electrification options require such significant power capacities that the absence of grid expansion will still result in overloads in 63% of simulated cases.

11.2. Recommendations

Based on the analysis of the load data, it has become evident that load coupling can offer significant advantages. It is crucial to encourage companies to seek collaborative opportunities. From conversations with experts at the Port of Rotterdam and in the industry became apparent that most companies are oblivious to the activities of neighbouring firms. Integration solutions start by establishing connections and gathering insights into the possibilities. For companies willing to look into an energy hub an important step involves companies measuring their electricity consumption. Continuing, the second step is gaining insight into the network topology to identify which companies are connected to the same 'ring'. Grid operators, for HIC Rotterdam Stedin in particular, play a pivotal role in this process. The blueprint established in the MOOI EIGEN project describes further steps that can be taken to successfully build an energy hub [18]. Suggestions for governance types, sharing data and legal frameworks among other topics are part of the blueprint. Furthermore, exploring alternative forms of collaboration beyond electricity has proven fruitful, as evidenced by multiple success stories. Great examples on steam exchange can be found in the HIC Rotterdam [53, 133]. Therefore, fostering a culture of collaboration and exploring diverse opportunities for partnership can enhance the efficiency and sustainability of energy usage among businesses.

The mapping exercise conducted on electricity generation units has revealed a promising avenue for providing flex capacity. With over 3600 MW of installed capacity situated in the HIC Rotterdam, there is significant potential for leveraging these units. It is recommended that the Port of Rotterdam as driver for innovation, in collaboration with grid operators and unit operators, explores the feasibility of integrating an industrial energy hub with an electricity generation unit. Such an integration should consider both the technical requirements needed for the seamless integration and the operational requirements for sustained functionality. While it is established that all units possess sufficient capacity to supply electricity to nearby clusters, practical application necessitates a thorough investigation into operational limits. Additionally, gaining insights into the responsibilities concerning the supply of electricity to the national grid is imperative to understanding the feasibility of integration.

The results of the scenario evaluation showed that grid expansion is a crucial factor in the success and speed of electrification of the HIC Rotterdam. Efforts are already made on accelerating the construction of electricity infrastructure, as is evidenced by one of three pillars in the National Grid Congestion Action Program [85]. The outcomes support this initiative by providing calculated evidence for its relevance.

11.3. Future Research

The research described in this report can be enhanced by collaborating closely with industrial stakeholders who can provide detailed insights into their operations. The methods used in Chapters 6-9 can benefit from extended data and expert insights. Engaging with these parties will not only offer a deeper understanding of the intricacies of their operations but also foster active participation in the development and evaluation of scenarios. Their expertise and firsthand knowledge can significantly enrich the research process, ensuring that the scenarios developed are both realistic and relevant to current industrial practices. This collaborative approach will enhance the robustness and applicability of the findings, bridging the gap between theoretical analysis and practical implementation in the industrial sector.

In continuation of this research an analysis focusing on specific load reduction along with capital and operational costs could offer valuable insights. Evaluating the cost-effectiveness of various capacity expanding measures could provide a more nuanced understanding of the tradeoffs involved in establishing an energy hub. To evaluate this, it would be essential to make informed predictions about the trajectory of costs in the future. If well-founded estimations can be formulated regarding potential price levels, an EMA model could serve as a valuable tool to assess different solutions. This model would facilitate understanding the cost implications of various solutions under different scenarios of cost and benefit developments. Another metric that could be researched in addition to this research are the CO_2-emissions associated with different congestion mitigation solutions. One of the most prominent solutions from this research, the integration with an electricity generation unit, depends on the use of fossil fuels. Doubts about the net value to emissions of this solution can be confirmed or refuted based on the outcomes of this research.

Another interesting topic to research relating to this project is the balance between security of supply and CO_2-emissions. The main task of grid operators, maintaining a stable grid, has always been of great value to our society. However, for a society in transition it is worth evaluating if performance metrics that previously led to societal benefits still have the same effect. Especially, now that security of supply and reduced emissions contradict each other in some cases. For instance, the installation of e-boilers in the HIC Rotterdam to supply heat without burning fossil-fuels is currently unthinkable as the grid can not transmit sufficient electricity to supply the necessary power levels. The easy alternative would be to continue using natural gas boilers. Research into the effects of reduced security of supply, especially in relation to reduced CO_2-emissions could provide valuable arguments to this discussion.

11.4. Reflection

Reflecting on the progression of this research, there are several aspects that I could have approached differently and should have addressed more effectively. These points can be consolidated into two main topics.

Firstly, there were multiple instances throughout the project where I should have focused more promptly on assessing the viability of a chosen research path. On several occasions during the research process, I embarked on developing a research direction without adequately evaluating whether it would yield fruitful results. While I consistently adhered to a constructed methodology, there were instances where I lacked a clear understanding of the intended outcome or the means to achieve it. For instance, the initial intention behind the cluster selection was to develop multiple configurations based on a range of potential building blocks. However, after filtering the compiled list, only the electric generation unit remained. Seeking expert input earlier could have generated a quicker selection of a specific case or provided insights into the feasibility of various components in a swifter manner.

This ties into the second learning point of this project, which pertains to defining the scope of the research. In this study, I investigated the current state of congestion in the Netherlands, particularly in the HIC Rotterdam, conducted an inventory of potential energy hubs in the HIC Rotterdam, and subsequently developed a model in order to simulate scenarios for the system. Within the scope of a thesis project, it might have been a better approach to either explore the formation of energy hubs in the HIC Rotterdam to alleviate current congestion issues, supported by academic substantiation through an analysis of several cases. Otherwise, a research focusing on a single industry cluster from the beginning. This cluster could then be scrutinised as to model its operation after which scenarios for its evolution could have been designed and simulated using EMA. The combination of these two approaches made it challenging to complete all phases satisfactorily. It is worth noting that both of these variations, like the current research, would have been impeded by limited availability of data and expertise. Nevertheless, in the early stages of the project more decisive choices could have been made to help the project's progress.

In hindsight, a more focused approach to assessing research paths and defining the scope could have resulted in a more streamlined and potentially more impactful study. These reflections underscore the importance of early evaluation and clear scoping in a research project to maximise effectiveness and efficiency.

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A

Additional background

In this chapter further background information can be found, in addition to the knowledge presented in Chapter 1. Subjects elaborated on are the historical development of the dutch electricity grid, grid issues other than grid congestion, technical solutions to congestion in general and for the HIC Rotterdam, an elaboration on the energy hub concept as well as the historical development of the HIC Rotterdam.

A.1. Dutch electricity grid

A.1.1. Historical development

The first public electricity supply in the Netherlands was commissioned in 1884 in Rotterdam. An accumulator (battery) was used to provide light to a block of houses. Electricity consumption in the early period focused on lighting, especially in hotels and department stores, as a novelty to attract customers, and in factories and railway stations. In the early period, it was mainly private individuals who took initiatives to set up electricity facilities around the country. Rotterdam was the first municipality to take charge of electricity supply in 1895. Other municipalities followed at the beginning of the twentieth century. Electricity supply centralised further as municipal power companies merged into regional and provincial power companies. In 1949, these regional power companies united to form the Cooperating Electricity Producers (SEP in Dutch). TenneT, SEP's successor, emerged in 1998 when it is designated in the new Electricity Act as the independent operator of the national transmission grid [180].

Before 1998, utilities were allowed to own an electricity network and sell the electricity simultaneously, which gave companies that owned the network unfair advantages over companies that were only active in the retail sale of electricity. This Act demanded the decoupling of utilities and electricity supply. The generation and retail of electricity in the Netherlands were liberalised. However, the transmission and distribution were and are still centralised and operated by the system operator and the utilities. The system operator and utilities have a monopoly position in the energy market. Therefore, these parties have to be regulated to guarantee the rights of consumers and businesses in the electricity sector. The Authority for Consumers and Markets was founded to this end in 2013.

The electricity grid handles the transmission of electrical energy from the international level to the local level where consumers are individually connected. To make this possible, all electricity networks at local, regional and national level are interconnected to form an interconnected electricity supply system. In this system, a distinction is made between the transmission function and the distribution function. At the national level, the transmission grid handles power transmission. Connections to the grids of neighbouring countries also belong to the transmission grid, as well as power plants and the supply points of distribution grids. A distribution grid distributes electrical energy within a region to all connected parties. Distribution grids are more branched than transmission grids and can be seen as the 'capillaries' of the electricity supply system [128]. Distribution system operators are responsible for the distribution of electricity from the transmission grid to local consumers; houses, stores and industry with a low or medium power demand.

The transmission system operator, TenneT, is the only stakeholder responsible for managing the high-voltage grid in the Netherlands, consisting of power lines with a voltage between 110 and 380 kV. The distribution grid is owned by six utility companies: Cogas Infra en Beheer, Enduris, Enexis, Liander, Stedin Netbeheer, and Westland Infra Netbeheer. They manage all powerlines with a voltage lower than 110 kV.

The current energy system in the way it is described in the Electricity Act is based on a grid that facilitates to users and the market. Where users may assume three market freedoms: freedom of connection capacity, freedom of transaction and freedom of dispatch. These market freedoms are often referred to as the 'copper-plate' principle. Referring to the electricity grid as a big copper plate, on which anyone can feed or take power, without restrictions. This principle is largely facilitated by the N-1 criterion in the Electricity Bill 1998, enforcing a redundancy in grid infrastructure so that if any component fails electricity can still be transmitted from every point A to every point B [37]. Adherence to the 'copper-plate' principle is exemplified by TenneT´s historically high availability percentage, achieving 99.99963% availability in 2022 [16].

A.1.2. Other grid related issues

Apart from congestion issues a power grid can face many different challenges. In the light of a changing energy system these new forms of energy generation impose multiple challenges. As discussed in Section 1.2.2 the increased implementation of renewables results in power system stability challenges.

Power stability

Frequency stability is one of the challenges that comes when synchronous generators with inertial response are replaced with DC power generating RES. Fortunately, the Dutch power grid is interconnected with the Continental Europe Synchronised Area (CESA). This is the 50 Hz phase-locked interconnection between most of Europe, the UK, Turkey and some North African countries. Since the electricity grid is interconnected over such a vast network frequency stability is not an issue (personal communication, 2023). Voltage level is another issue that might arise when DER, especially solar PV is added to the generation portfolio. Furthermore, capacitive coupling is a power system issue that occurs when two cables are aligned too close to each other. This coupling effect causes challenges for grid operators in case limited space is available for infrastructure.

Spatial congestion

This introduces another congestion problem, spatial congestion. Due to a high density of energy infrastructure in some areas the space available underground for cables and pipes is increasingly limited. If grid operators theoretically would have capacity for new installations on their distribution grid, a challenge remains how to establish a physical connection. In the meanwhile, further electrification and expansion will cease without effective congestion management, hampering the region's energy development and sustainability goals. National goals of connecting 21 GW of wind power will also stagnate since a significant portion of wind power is set to come ashore at only a few locations. Converting this electricity to other forms of energy like hydrogen or ammonia could allow for the distribution of this clean energy. The problem with these forms of energy is that they cannot be distributed and stored in the same ways conventional energy carriers could. A transition to industries that require alternative energy carriers results in an increased space demand. This is because these alternative fuels are often less energy-dense. For example, hydrogen and biomass have an energy density of approximately 10 Nm^3 and 20 MJ/kg respectively, while natural gas and oil have an energy density of 30 Nm^3 and 40 MJ/kg respectively. This lower energy density leads to larger volumes being required for the same amount of energy.

Though these issues require significant efforts in order for society to decarbonise, this research project focuses on the challenges associated with grid congestion.

A.2. System solutions

Chapters 1 and 4 already talked about solutions to grid congestion. In addition to the solutions mentioned there, more solutions exist that can help mitigate grid congestion.

Originally, grid congestion was tackled through grid expansion. However, infrastructure project are characterised by long lead times. Furthermore, investing in additional transmission capacity in some cases, especially where there are large peaks at single points in time, is not the most efficient solution to facilitate the transmission capacity requested by the market. This led to the construction of the consideration framework for grid operators called ’expand unless’ by the Consultative Table Energy (OTE in Dutch) [169]. The framework urges grid operators to also look at alternative solutions that add flexibility to the system. These comprise partly of the technical measures discussed in Sections 1.2.4, the utilisation of technical measures in the HIC Rotterdam is described in 4.2.2. Other solutions applied by TenneT are the temporal utilisation of redundant infrastructure and dynamic line rating (DLR).

Important to note is that congestion is a temporal phenomenon. The congestion discussed in this chapter typically only occurs for a few hours throughout the year. However, due to the inherent properties of the electricity grid, overloads can cause immediate faults. The power grid must therefore be dimensioned to handle peak demand. Because the power grid is such critical infrastructure the grid is operated according to the N-1 criterion. Meaning the failure of a single grid element does not result in disruptions to the supply at consumers [84]. However, now that the limits of the power grid’s capacity are approached this criterion is occasionally waived. Since 2022, TenneT has started to employ this redundancy to facilitate transmission capacity for renewable energy generation, primarily from solar parks. This provided up to 30% extra capacity in a number of places. Currently, this method is exclusively applied to renewable energy generation sites since these are designed to cope with intermittent generation [173].

DLR is the active monitoring of weather conditions to vary the thermal capacity of overhead lines. The transport of electricity heats the conductors through which the current flows. This heating causes conductors to sag, limiting the maximum transmission capacity of a high-voltage connection. However, weather can have a beneficial effect on the cooling of conductors. At low temperature, but mainly due to wind, the line is cooled more, resulting in less sag. In such a case, more current can therefore be transported. With the Dynamic Line Rating technique, the sag and transport capacity of a number of critical line segments of the power line are determined every five minutes in a direct manner. Based on this measurement data, the amount of additional transmission capacity over the line can be determined [34].

An alternative solution that is often suggested by literature and business papers is to include flexibility in the form of Battery Energy Storage Systems (BESS). These systems can rapidly and reliably inject or withdraw power through electrochemical conversion, allowing them to participate in imbalance markets. However, as outlined in Section 1.2.4, employing a BESS in imbalance markets aggravates the congestion issue. Considering both the advantages and disadvantages, this multi-functionality leads TenneT to regard BESSs as ’net-neutral’ in their calculations (personal communication, 2023).

A.2.1. System solutions in HIC Rotterdam

In the HIC Rotterdam some technical measures can be employed to reduce grid congestion. Section 4.2.2 mentions the presence of a capacitor bank, phase shifter and the possibility of grid reconfiguration. These measures are explained in the following paragraphs.

Capacitor bank

A capacitor bank is present in the grid of the Botlek region. This is a system consisting of several capacitors connected in series or parallel to form an energy storage system. By storing electric charge a capacitor bank is able to provide voltage regulation, harmonic filtering or power factor correction of which the latter is relevant for the congested grid. By adding or subtracting reactive power the capacitor bank is able to increase the capacity factor thereby reducing line losses and improving system efficiency. In short, the amount of useful power transported over the line is increased.

Phase shifter

A phase shifter or phase shifting transformer (PST) is an example of a Flexible AC Transmission System, a family of modern controllers able to perform power control [170]. In the connection Europoort-Theemsweg a phase shifter is included. By controlling the phase shifter the amount of available power can switch between lines Botlek-Geervliet and Maasvlakte-Europoort. This technical measure can help relief the grid at times when one of both connections is overloaded. However, if both connections are overloaded this control action does no longer help.

(Temporal) shifts

Corrective switching was already proposed as a means to alleviate grid overloads in 1980 [79]. Reconfiguration is an interesting solution since it allows grid operators to alleviate overloads by altering the grid topology instead of costly generation or load curtailments. In the HIC Rotterdam TenneT might also see the need for network reconfigurations, hereby changing the grid topology.

A.3. Concept of an energy hub

Energy hubs can play a pivotal role in addressing the multifaceted challenges posed by the evolving energy landscape. An energy hub is described as the place where the production, conversion, storage and consumption of different energy carriers takes place [112]. In an energy hub streams of electricity, heat, hydrogen, steam, and other forms of energy can be connected between companies. Applying this to an industrial cluster allows for optimal use of the energy carriers available. Local electricity generation fits neatly into the energy hub concept as well. Wind or solar PV power on-site can supply an industry cluster with green energy, limiting the required grid connection. The problem with grid stability can be alleviated by including flex solutions with fast response times in the energy hub, such as battery storage systems. Even the large amounts of electrical energy from the North Sea benefit from the concept of an energy hub. Converting electricity from wind parks to other energy carriers relieves the pressure on the electricity grid.

A.3.1. Origin

In 2005 the energy hub concept was first presented by a research team at the Power Systems and High Voltage Laboratory at ETH Zurich within a framework of the project called “a vision of future energy networks”, later referred to as the VOFEN project. The project aims to figure out the shape of energy networks in the long term horizon (30-50 years). As a result of the VOFEN project an energy hub concept was introduced for the first time and was defined as an interface between consumers, producers, storage devices and transmission devices in different ways: directly or via conversion equipment, handling one or several carriers [43].

This definition has largely remained the same over the years. In [112] different concepts are reviewed after which the definition of an integrated energy hub is described in the following way: The integrated energy hub is a multi-generation system in which production, transmission, storage and consumption of multi-energy carriers take place to meet different type of demands. This definition has been widely adopted by both academic literature [127] as well as governments and the business world [109] as the common definition for an energy hub. ’Transmission’ is often replaced with, or accompanied by, an extra term ’conversion’ as different energy carriers can be converted from one to another to meet the different types of demand. Some literature refers to an energy hub containing multiple energy carriers as a ’hybrid energy hub’. Given the definition for an energy hub as stated above, this will be referred to simply as an ’energy hub’.

A.3.2. How does an energy hub work?

Now that an understanding is developed of what purposes an energy hub might fulfil, the features that allow it to do so are explored. As explained previously an energy hub is built around four features; production, conversion, storage and consumption. These four features and how they contribute to the energy hub are discussed. Possible components for each of the features are listed and highlighted in the diagram in Figure 1.1.

Energy production

The energy hub model incorporates various energy resources, including RES, the electricity network, the natural gas network, and heating networks, to meet diverse consumer demands. Inputs are shown on the left side and top of the diagram in Figure 1.1. These resources can serve as inputs for the energy hub model [103]. Traditional energy generation plants, such as thermal power plants, exhibit low energy production efficiency, along with losses during energy transmission and distribution, resulting in substantial energy wastage. For instance, in a typical coal thermal power plant, only 28% of primary energy reaches residential consumers [124].

Energy hubs can facilitate distributed energy resources (DER) located near consumption sites. This offers advantages such as reduced energy costs, diminished transmission and distribution losses, and improved energy efficiency. DER systems include technologies like fuel cells, waste heat recovery equipment, and RES like PV systems and wind turbines. These systems produce energy in the form of diverse carriers, such as electricity, heat, and hydrogen, using sources like solar energy, wind power, and geothermal energy. Also, biomass can be employed to generate electricity, heat, and transport fuels. Achieving 100% renewable energy systems in Europe by 2050, as discussed in [30], is feasible through current technologies, highlighting the critical role of energy hub models in this transition.

The most utilised energy carriers are electricity and natural gas [112]. However with electricity transport becoming more and more constraint and industries shifting away from fossil fuels, other energy carriers can form a solution. Hydrogen emerges as a clean energy carrier within energy hubs, offering potential in various energy sectors. Utilising surplus energy from offshore wind parks presents cost-effective prospects for renewable generation based hydrogen production. Furthermore, in energy taxation, hydrogen consumption is now taxed the same as natural gas consumption. Together, with a higher production price for hydrogen makes that there is no financial incentive to replace natural gas with hydrogen in energetic applications. Technological innovation will aim to decrease the cost of hydrogen production. In addition, in the near future hydrogen use in energetic processes will be taxed at a lower rate than natural gas in the Dutch energy tax [179].

Waste can also be a promising energy hub input. Using waste for energy production leads to reduced emissions, enhanced energy efficiency, and improved waste management. Possible streams that can be recycled are residual heat, organic waste streams or plastic waste that can be transformed to pyrolysis oil [15, 17]. However, for energy hubs to drive sustainable energy systems, long-term dependence on fossil fuels like electricity and natural gas, coupled with infrastructure challenges, presents limitations. The energy hub paradigm calls for embracing alternative sources, especially RES. Energy hub models should transcend traditional resource integration and encompass sustainable and clean sources. These elements facilitate energy hubs in the integration of energy infrastructure and harness the synergy among diverse energy carriers, thus shaping the future of sustainable energy systems [167].

Energy conversion

As seen in the previous section, an energy hub can be fed from various sources. Some of these inputs can be transferred to the output without any conversion and others can be converted to energy carriers like electricity, heat or hydrogen. Depicted in Figure 1.1 by the blue and red diamonds. Boilers, electric machines, gas turbines, micro turbines (MT), pumps, transformers, inverters, and heat exchangers can be used to modify the input sources to a usable quality, quantity and mode [43]. Boilers mainly have been used as additional energy supply alongside CHP-systems to compensate for the lack of recovered heat when demand of heat is high. It is thus the most widely used in energy hub models after the CHP-system [112]. The transformer has been mainly used to convert electricity purchased from the grid to usable voltage amounts and it represents the dependence of energy hub models to the electricity network. Heat exchangers have been commonly used alongside heating networks. An interesting application of heat pumps is using them to convert excess electricity into thermal energy and storing it in thermal storages. This leads to reduced operating costs and greater flexibility of a system. Another sustainable fuel, biomass, has been used in energy hub models in the form of biomass boilers, biomass reactors, and gasification reformers for the production of heat, electricity and biofuels respectively.

Many converters mentioned above are used to only convert one type of energy carrier. However, energy hubs are designed to make use of various energy carriers to meet different demands. Therefore, energy hub models benefit from systems, which can use a single energy carrier to meet more than one demand. As these systems result in increased efficiency, reduced primary energy consumption and thereby costs of the system. An example of such a system is the CHP-system. A CHP-system simultaneously produces electricity and heat from a single energy source. CHP-systems have seen their popularity increase because of their high efficiency and their flexibility to meet different demands [112, 166]. In most cases, a CHP-system has the role of supplying electricity demand complementary to a connection to the main electricity grid. In times of low demand, electricity can be supplied from the network. At times of high demand and high electricity prices, electricity can be produced by the CHP-system, helping to balance the grid.

A promising renewable conversion system is a fuel cell (FC in Figure 1.1). Part of why it is so promising is its ability to use many fuels as input. Hydrogen, biogas, methanol, natural gas can all be fed as input. In a hydrogen-fed fuel cell, electricity, heat and water are produced from hydrogen and oxygen.

More advantages of the fuel cell are lower emissions and environmental pollution, higher efficiency, easy installation, reliable operation [107], decentralised and distributed energy generation, possibility of producing its fuel such as hydrogen in any place from electricity and water, possibility of using renewable fuels, and most important of all multi-generation possibility [147]. However, the fuel cell faces serious challenges such as high cost, low power density, and durability. Electrochemical reactions in the fuel cell release a significant amount of heat. The recovery of this heat for applications such as space heating, provides the possibility to use the fuel cell as a CHP-system.

Energy storage
An integral part of an energy hub is an energy storage system (ESS), shown on the top in Figure 1.1. An ESS can capture energy at times it is not needed for use at a later stage. Especially when RES is included, as RES are hard to control and schedule due to their intermittent nature which shows often the inverted pattern of the daily demand. Adding an ESS to a system with RES facilitates the integration of the RES and increases the reliability in off-grid mode. The use of an ESS converts RES to a dispatchable source.

Historically, thermal and electric storage have been most widely used [112]. This is mainly due to the low initial capital cost of thermal storage and fast response time of electric storage [122]. Other ESSs include hydrogen (shown on the bottom in Figure 1.1) and gas tanks, compressed-air and pumped-hydro storage, flywheels or capacitors. The choice of using an ESS in the energy system should be made with three goals in mind [112]; facilitating the integration of RES, increasing system reliability and optimising system performance through the use of smart energy systems.

Traditional power grids, which were mainly based on synchronous machines, have a spinning rotor which works as potential spinning reserve to respond to rapid changes in demand. In the RES-based systems, this imbalance can play an important role in system reliability. ESSs can be used in power systems for ancillary services in order to improve system conditions, the quality of power, and solving problems related to its stability. Some of the advantages of using an ESS in power systems can be described as the improvement of the network inertia to respond to fluctuations, frequency regulation, voltage regulation, reducing volatility, preserving the network synchronisation, providing direct voltage in the case of faults, providing the necessary energy to black start, providing spinning reserve, and hereby reducing the need for more balancing infrastructure.

Another application of an ESS is the realisation of smart energy systems. Using a local ESS on the demand side with smart technologies for demand-side management programs optimises the use of equipment and resources. An ESS can be used for demand side management actions like load shifting, as will be explained in the following paragraph on energy consumption. Stored energy from off-peak periods can be used in on-peak periods and allows for delayed sales to the energy market, based on energy prices. This is in addition to the reduction of system operating costs from peak shaving and improving the load curve. In the optimal control of an ESS, many factors such as technical constraints, anticipated production capacity, energy markets, energy pricing plans, demand, weather conditions, etc. must be considered.

Energy consumption
The final aspect of an energy hub is the energy consumption. As discussed, energy can be consumed through various energy carriers. Most energy hubs do this via electricity, heat or hydrogen [112]. The arrows on the right in Figure 1.1 depict the loads. Almost all planning and management activities in the energy system are for coordinating the production and consumption pattern. Given the ambiguous nature of demand due to uncertainty in consumer behaviour, demand forecasting for different time periods has always been one of the main challenges in energy systems. The lack of detailed forecasts of demand often leads to an unrealistic model of the system and can lead to problems such as capacity shortage, reliability and even instability of the entire system. Therefore, the effects of the energy demand profile on the overall system performance should be considered in planning. Traditional energy management systems were based on the production side management. Problems related to the increase in demand and sudden changes in the system have mostly been compensated by increasing production capacity. However, increasing capacity is not a viable solution anymore, as energy demand increases faster than capacity can be installed.

A solution to this problem is demand side management (DSM) or demand response (DR). To relieve grid congestion multiple solutions can be applied. With an increasingly volatile energy system it is important that all actors contribute to a robust grid. From the producer side actions such as curtailment can be taken. The operator might help in expanding network capacity. Then there is the consumer side which can help by offering demand side management. A few examples of DSM features are load growth, energy savings, energy efficiency and demand management programs. These focus on reducing the required energy or influencing the pattern of consumption over time. Examples of demand response strategies are peak shaving, valley filling or load shifting. All are different methods to balance a consumer's demand profile. The flexibility becomes even greater when multiple energy carriers are involved. When multiple energy carriers are present, the energy carrier with the lowest cost or more efficient converters can be used at all times. This should, on the other hand, outweigh the increased cost of the system, as infrastructure is needed for the different energy carriers. Industry has historically been a sector with a standard consumption profile with little deviations. This will need to change to facilitate the energy transition.

A.3.3. Scope

The spatial scope of an energy hub can vary greatly between projects. The term energy hub can already be used for an integrated energy system within a single building. In such a case the electricity network might be interconnected with the heating and cooling network and the building might have a battery installed making it comply with the four energy hub features [22]. An example of such a system is the Regionalwerke AG Baden in Switzerland which is often cited as the first energy hub. Here the different energy flows within a single municipal utility are connected [50]. Conversely, an energy hub can also be as big as an entire country. Since the national electricity and gas grid span across the entire country and are interconnected, they initially form the basis of a vast energy hub. In the future the hydrogen network might be connected to the other grids as well. Gasunie already uses this terminology in their promotion of the Netherlands as 'European hydrogen energy hub' [46]. However, this definition does not hold completely since this integrated network is not centrally coordinated. The most common spatial distribution of an energy hub is that between a number of companies located in a single area [127]. In such a case companies can connect their electricity connections if they are situated under the same substation. These types of energy hubs can be further subdivided into residential, commercial, agricultural and industrial energy hubs [113]. Respectively a neighbourhood, block of offices, group of farm-related processes or industry-parties can be grouped to form an energy hub. Since this thesis focuses on companies within the Harbour Industrial Complex Rotterdam, the scope can be described as an industrial energy hub.

A.3.4. Control

Since an energy hub incorporates many system components that are interconnected, the need arises for an energy management system (EMS). This EMS can control the energy flows present within the energy hub. In general, two coordination frameworks can be distinguished; a centralised and a decentralised mode. In the centralised mode, a service provider is responsible for the optimisation of optimal energy flow amongst all participants, while in the decentralised mode, each company is in charge of its individual controllable units to participate in the local P2P market for the individual benefit [176]. At pilot projects in the Netherlands the centralised mode is used more often. In 2022 at Schiphol Trade Park an e-hub was establishment with a central energy service provider [137]. A project in cooperation with DSO Stedin started in September 2023 where a central organisation manages the energy flows of the companies enlisted to the cooperation [155]. Although both do not fulfil the requirements of an energy hub, since only electricity is used as an energy carrier, the pilots show the entrepreneurial way of thinking applied in the Netherlands. Since a general framework is missing and there is little experience on energy hubs a collaborative approach is preferred.

A.3.5. Similar concepts

When examining the topic of energy hubs in both academic literature and business papers, the term is commonly used to describe projects with varying characteristics. Similarly, multiple expressions are employed for the energy hub concept: energy system integration, multi-energy system, integrated energy system, utility sharing or multi-commodity hub, among others. To establish a clear distinction between this research' subject and related concepts, concepts similar to that of an energy hub are discussed below.

Microgrid
The concept most often used similarly to that of the energy hub is the microgrid. Many articles, reports and press releases use the term microgrid interchangeably with energy hub. A key difference separating both terms however is the energy carriers present in the system. For a microgrid the system consists solely of electrical connections, while an energy hub by definition connects multiple energy carriers by utilising conversion equipment. Another characteristic that sets the microgrid apart form the energy hub is the possibility to operate a microgrid in standalone mode, having no connection to the grid. Examples of pilot projects at Schiphol Trade Park and REC Tholen are both examples of microgrids, these will be discussed in Section 2.1. If in the future multiple energy hubs would be interconnected, they might be referred to as meso-grids. For example in the case the HIC Rotterdam would be interconnected into a single energy hub. Another term that emerges in the communication on energy systems is cable pooling. Cable pooling applies the microgrid concept to RES, often solar PV.

Closed distribution system
In the Netherlands a common term for a collaboration on energy systems is that of a closed distribution system (CDS) or 'Gesloten distributiesysteem' (GDS) in Dutch. The CDS is a classification recognised under dutch law of a private electricity and/or gas network with a further set of conditions. The CDS has a grid connection and operates on a local scale. A CDS might be the same as an energy hub or might include an energy hub within its system.

Virtual Power Plant
Similar to the microgrid is the virtual power plant (VPP) in the sense that only electricity flows within the system. The difference between both is that a microgrid is connected locally with direct connection between participating companies. Whereas a VPP is essentially a microgrid that is only virtually connected and can inhibit parties over a large geographical area. A VPP can be initiated to balance demand profiles in order to limit the load on the overarching grid.

Industrial symbiosis
Another concept that is closely aligned to that of the energy hub is that of 'industrial symbiosis'. Used to describe an approach where waste from one industrial process can serve as the raw materials for another, thereby reducing the impact of industry on the environment [44]. Both energy hubs and industrial symbiosis share common goals like resource and economic efficiency and aim to do this through collaboration between various stakeholders.

Prof. M.R. Chertow from the Yale School of Environment whose research has been a driving force in the exploration of the industrial symbiosis concept, introduces a criterion that can be applied to both industrial symbiosis and energy hubs. The 3-2 heuristic stipulates that at least three different entities must be involved in exchanging at least two different resources to be considered a basic type of industrial symbiosis. By involving three entities, the 3-2 heuristic begins to recognise complex relationships rather than linear one-way exchanges [26].

While sharing similarities, both concepts inherently differ from each other. Energy hubs focus on creating a resilient energy system by introducing flexibility and diversifying energy sources. Industrial symbiosis focuses more on optimising the use of materials, thereby reducing waste. Also on scope both concepts typically differ, due to the different resources to optimise. Optimisation of material use is usually confined to a local industrial cluster, whereas in theory energy systems can be integrated on regional or even national level. As is explained in the previous subsection. Some examples exist of articles labelling projects on regional scale as industrial symbiosis thereby blurring the distinctive features of both concepts [80]. Both phenomena also tend to originate differently. The energy hub is envisioned beforehand as the intricate interaction of the various components create flexibility. For industrial symbiosis a network might originate more organically. The industrial district in Kalundborg in Denmark has been dubbed as the first example of industrial symbiosis by academics. This project is not the result of a careful environmental planning process. Rather it is the result of a gradual cooperative evolution of four neighbouring companies and the Kalundborg municipality [54].

A.4. Port of Rotterdam

The Port of Rotterdam is the largest seaport in Europe, and the world's largest seaport outside of East Asia. From 1962, until 2004, it was the world's busiest port by annual cargo tonnage, but was overtaken in 2004. In 2020, Rotterdam was the world's tenth-largest container port in terms of twenty-foot equivalent units (TEU) handled, with a total of 467.4 million tonnes cargo in 2022 [1] [161, 70]. It has acquired this position by years of innovation and expansion.

The Rotterdam port originates from around 1250 when a dam was built in the river Rotte [52]. The village that developed was given the name Rotte-dam. In the 17th century the port began to further develop with the construction of ports close to the city. These were expanded in the direction of Schiedam and at the southside of the river in the late 19th century. The expansion of the port took flight in the 20th century. The petrochemical industry, still one of the most prominent in the port, first settled after the construction of the 'Eerste Petroleumhaven' at Pernis in 1929. The petrochemical industry further expanded to the Botlek area in 1947. The Suez Crisis in 1956 led to the scaling of tankers. Rotterdam capitalised on this development with the construction of the Europoort area, which was accessible to the largest ocean-going vessels. Consequently, by 1962, the port of Rotterdam had become the largest port globally. The construction of the Europoort meant the port now stretched from the city all the way to the sea, marking the culmination of expansion possibilities. Nevertheless, the hunt for spatial expansion continued.

The amount of ships attending the port grew in the second half of the 20th century, as well as there size, resulting in the need for spatial expansion. This led to the construction of an artificial landmass in the North Sea: Maasvlakte 1. Expansion continued in the 21st century with the latest project Maasvlakte 2, which was commissioned in May 2013. With this addition the total port area accumulates to 12,500 hectares. In this area the port accommodates approximately 120 industrial companies representing diverse sectors and activities. These activities make that the port area provides employment for 183,000 FTE and has an added value of 2.8% of the Dutch GDP. A study on the effect of the ports in the Rhine-Meuse area on the entire Dutch economy even estimated the total employment provided at 563,800 FTE and a total added value of 63 billion euro, equivalent to 8.2% of the Dutch GDP [20].

[1] TEU, twenty-foot equivalent unit, is a unit of cargo capacity based on a standard intermodal container with a length of 20 foot

B

Grid topology HIC

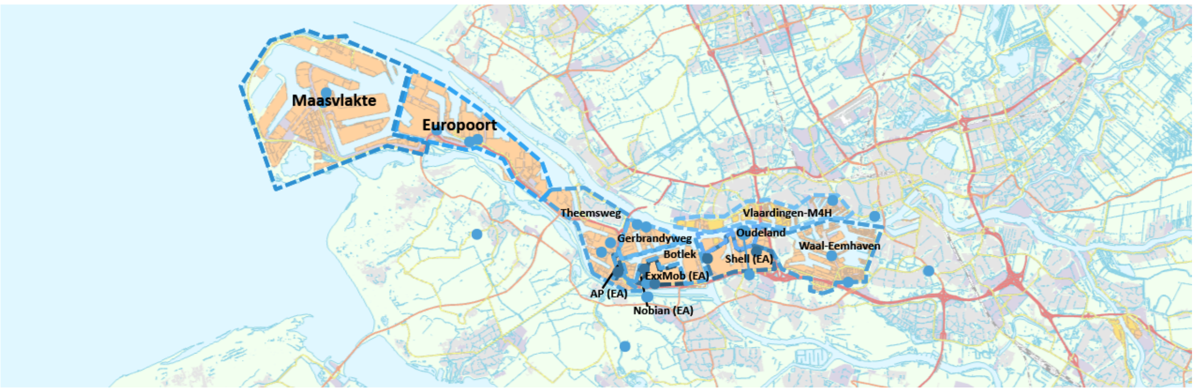


Figure B.1: 150kV substations (blue dots) and corresponding clusters (striped lines)

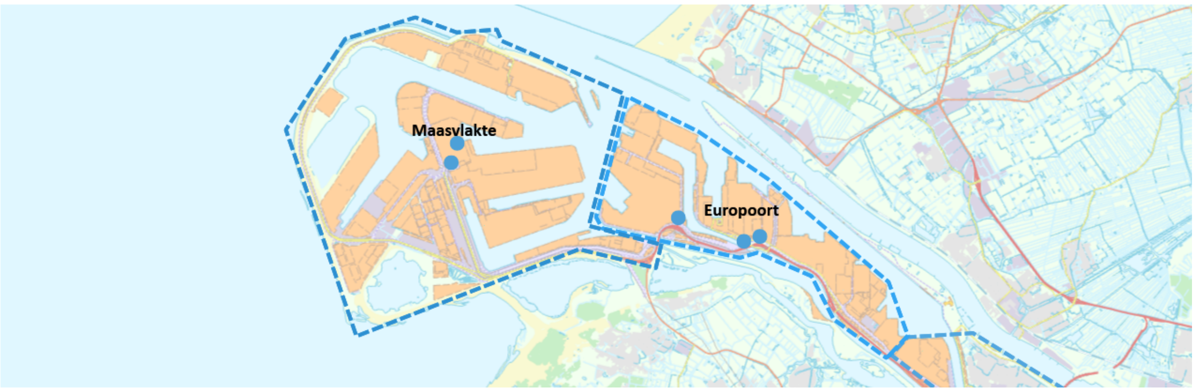


Figure B.2: Zoomed image of 150 kV substation in the Maasvlakte and Europoort areas

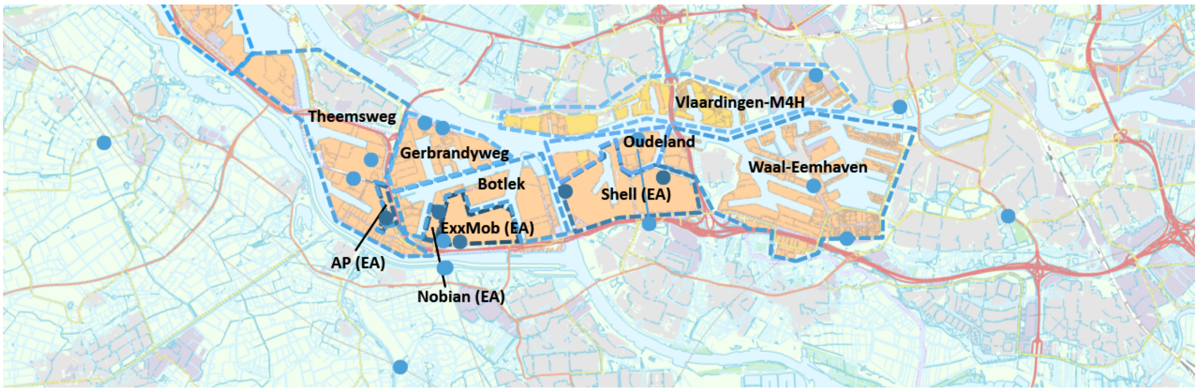


Figure B.3: Zoomed image of 150 kV substation between the Theemsweg and Waalhaven areas[1]

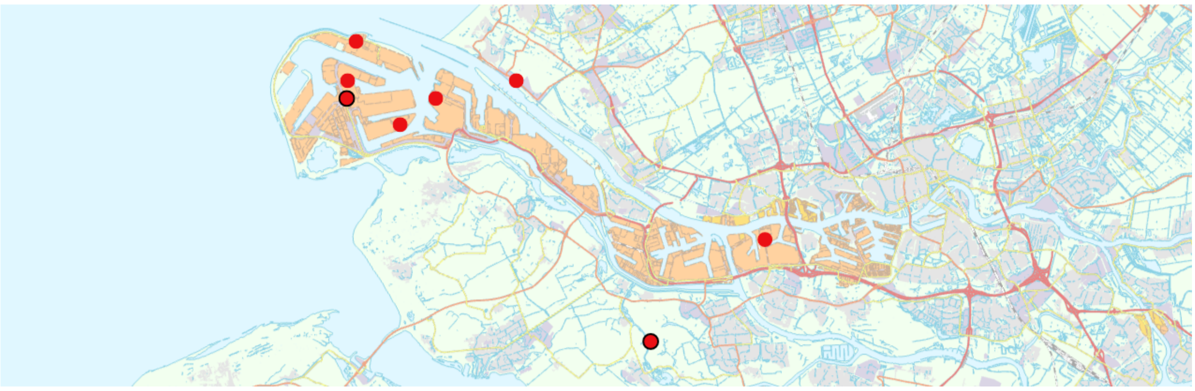


Figure B.4: 380 kV substation in the HIC Rotterdam (lined dots indicate connection to the national 380 kV grid)

[1]EA = Individual connection ('eigen aansluiting' in Dutch)

C

Energy hub technologies

In Chapter 5 a selection is made on components eligible for energy hub integration based on the components lists provided in that chapter. The component lists mentioned there are derived from the literature search on energy hub components. The output of this literature search is presented here in Tables C.1 and C.2. These tables also shows the power capacity and TRL of some of the components. Components that lack an indication for either or both are excluded on other criteria(s) already. The tables presented in Chapter 5 are concatenated as some of the components listed here are similar in use.

Table C.1: Overview of potential storage components for an energy hub

Type	Storage utilities	Energy in/output	Storage medium
Chemical	H_2-tank	H_2	H_2O
Chemical	Salt cavern	H_2	H_2O
Chemical	NH_3-tank	H_2	NH_3
Electrical	Supercapacitor	E	Electric capacity
Electrochemical	EV	E	Chemical
Electrochemical	Li-ion battery	E	Chemical
Electrochemical	Redox-flow battery	E	Chemical
Electromagnetic	SMES	E	Magnetic field
Latent heat	Ice storage	C	H_2O
Latent heat	Cryogenic air	H	Air
Mechanical	Flywheel	E	Rotational
Mechanical	Pumped hydro	E	Potential
Mechanical	CAES	E	Potential
Sensible heat	Molten salt	H	Salt
Sensible heat	Hot water	H	H_2O
Sensible heat	Hollow rock	H	Rocks
Thermo-chemical heat	Adsorption	H	Sorbent
Thermo-chemical heat	Salt hydrate (Cellcius)	H	Salt

C = Cooling, E = Electricity, H = Heat, H_2 = Hydrogen

Table C.2: Overview of potential conversion components for an energy hub

Type	Conversion technologies	Input	Output	Capacity (MW)	TRL
Biogas production	Pyrolysis	BM	BF, BG, SG	30	8/9
Biogas production	Anaerobic digestion	BM	BF, BG, H	5.5	9
Boiler	Natural gas boiler	NG	S / H	3-73	9
Boiler	Biomass boiler	BM	S / H	345	9
Boiler	H_2 boiler	H_2	S / H	1-300	8/9
CHP	CHP (turbine+ORC)	NG	E, H	24-900	9
Fuel cell	Solid Oxide FC	H_2 / M / NG	E, H	20	9
Fuel cell	PEM FC [a]	H_2 / M / NG	E, H	2	8
Fuel cell	Alkaline FC		E, H		<8
Fuel cell	Molten Carbonate FC		E, H		<8
Fuel cell	Posphoric Acid FC		E, H		<8
H_2 conversion	Haber-Bosch	H_2, N_2, NG	NH3		9
H_2 conversion	Haber-Bosch electric	H_2, N_2, E	NH3	8.5	8/9
H_2 production	Methane pyrolysis	CH_4	H_2		3/6
H_2 production	Partial oxidation	NG, BM, O_2	SG, S	350	9
H_2 production	Elektrolyser Alkaline	E	H2, S / H	1000	8/9
H_2 production	SMR [b]	NG	SG, S	300	9
H_2 production	Elektrolyser PEM	E	H_2, S / H	1000	8/9
H_2 production	Gasification	BM/C	SG, S	1000	8
H_2 production	TWSC [c]	H_2O, H	H_2		3/4
H2P	ORC low heat [d]	LT heat	E	5	9
H2P	ORC high heat [d]	HT heat	E	17.5	9
H2P	RTG [e]	H	E		3/5
H2P	RED [f]	H	E		2
Mechanical	Piezoelectric generator	Mechanical	E	0.001	8
P2H	Electrode boiler	E	S / H	90	9
P2H	Electric boiler	E	S / H	5	9
P2H	Heat pump	E	H	20	9
Renewable	Wind		E	3-15	9
Renewable	Solar PV		E	144	9
Renewable	Geothermal		E, H	8-15	8
Renewable	Hydropower		E	25	8/9
Renewable	Solar thermal		E, H	500	8
Renewable	Tidal energy		E	1.2	5/8
Renewable	OTEC [g]		E, H	100	4/5
Renewable	Wave energy		E		5/6
Rotary engine	Biogas turbine	BG	E, H	8	9
Rotary engine	Fuel/natural gas turbine	NG, H_2	E, H	500	9
Rotary engine	ICE [h]	NG	E, H	10	9
Rotary engine	Steam turbine	NG/BG	E, H	8598/740	9
Rotary engine	Ammonia turbine	NH_3	E, H	288	5/7
Waste	RIFT [i]	Iron powder	S / H	100	5/7
Waste	Waste incineration	Waste	S / H		9

BF = Biofuel, BG = Biogas, BM = Biomass, C = coal, CH_4 = Methane, E = Electricity, H = Heat, H_2 = Hydrogen, H_2O = water, M = Methanol, NG = Natural gas, NH_3 = Ammonia, S = Steam, SG = Syngas

[a] PEM = Proton exchange membrane
[b] SMR = Steam methane reforming
[c] TWSC = Thermochemical water splitting cycle
[d] ORC = Organic rankine cycle
[e] RTG = Radioisothope thermoelectric generator
[f] RED = Reverse electrodialysis
[g] OTEC = Ocean thermal energy conversion
[h] ICE = Internal combustion engine
[i] RIFT = Renewable Iron Fuel Technology

D Generating load profiles

In Chapter 7 scenarios are designed for an industrial cluster that is modelled in Chapter 8. Before these research phases can start however a model of the industrial cluster's electricity system needs to be made. Through a literature search a list of components is compiled that together make up the operation of a tank terminal. Combining literature data with information gathered from terminal operators gives insights into the power ratings of components and operating hours. These two characteristics are needed to generate a component's load profile. For each terminal a model is made that includes the number of components for each actual terminal. Due to confidentiality reasons these compositions are not shared in this report.

The generated load profiles are tuned by comparing the load duration curve (LDC) of the generated profile with the LDC of the measured load data. A validation is done using the LDC as it will not be possible to recreate an hourly copy of the measured data, since the hourly operation of a terminal is not predictable. To this research the LDC of a load profile is more interesting as the electricity load model is meant to calculate the overloads over an entire year. Furthermore, the characteristics of the generated load profile are compared to those of the measured load data by comparing their mean, median, standard deviation and skewness.

The generated LDC's for all four load models and their respective measured data are presented in Figures D.1-D.4. Tables D.1-D.4 show the comparison on the profile's characteristics respectively. For terminals 2-4 the generated LDC matches the measured data well, supported by the metrics. The mean is used to scale the power ratings of the components, therefore all four graphs score relatively well on this metric. Standard deviation for terminals 2-4 shows less than 10% difference highlighting similar characteristics. Skewness for terminals 3-4 can be regarded similar. For terminal 2 the measured load is skewed towards the half of the dataset with lower values. This is mainly caused by the long 'tail' of the graph, as can be seen in Figure D.2. For terminal 1 it proved harder to obtain a similar LDC. Partly, this is due to the fact that less insights were provided into the terminal's operation.

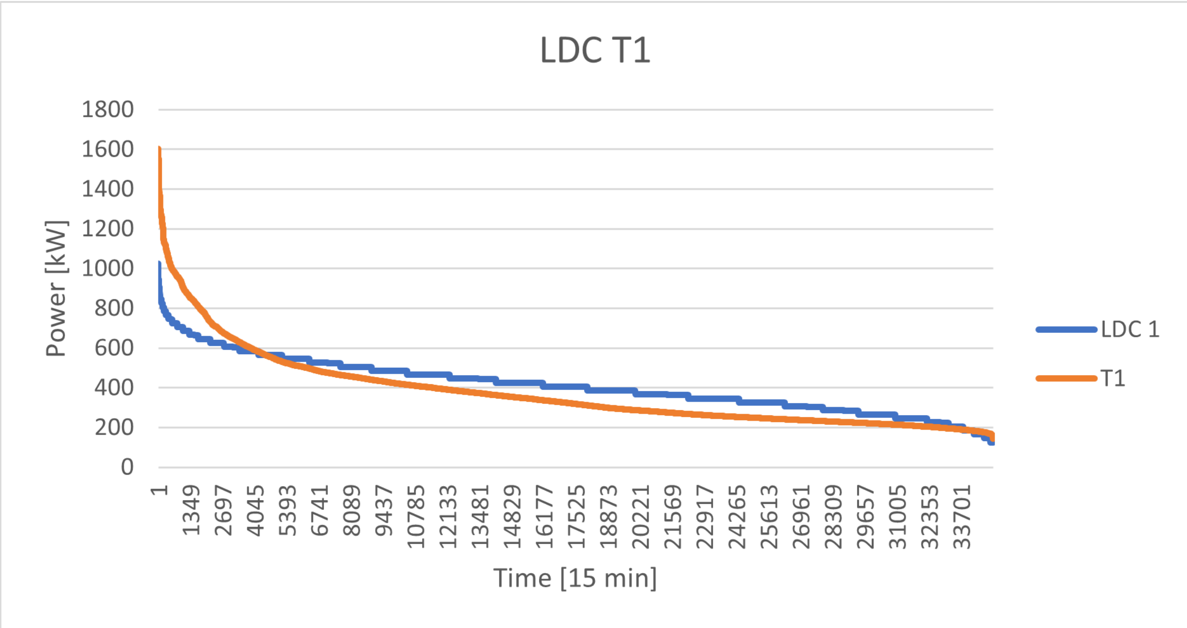


Figure D.1: Load duration curve of measured and generated load for terminal 1

Table D.1: Analysis on similarity between both profiles for terminal 1

Metric	Measured load	Generated load	Difference
Mean	377	412	-9.46%
Median	318	405	-27.24%
Std dev	194	135	30.3%
Skewness	1.95	0.481	

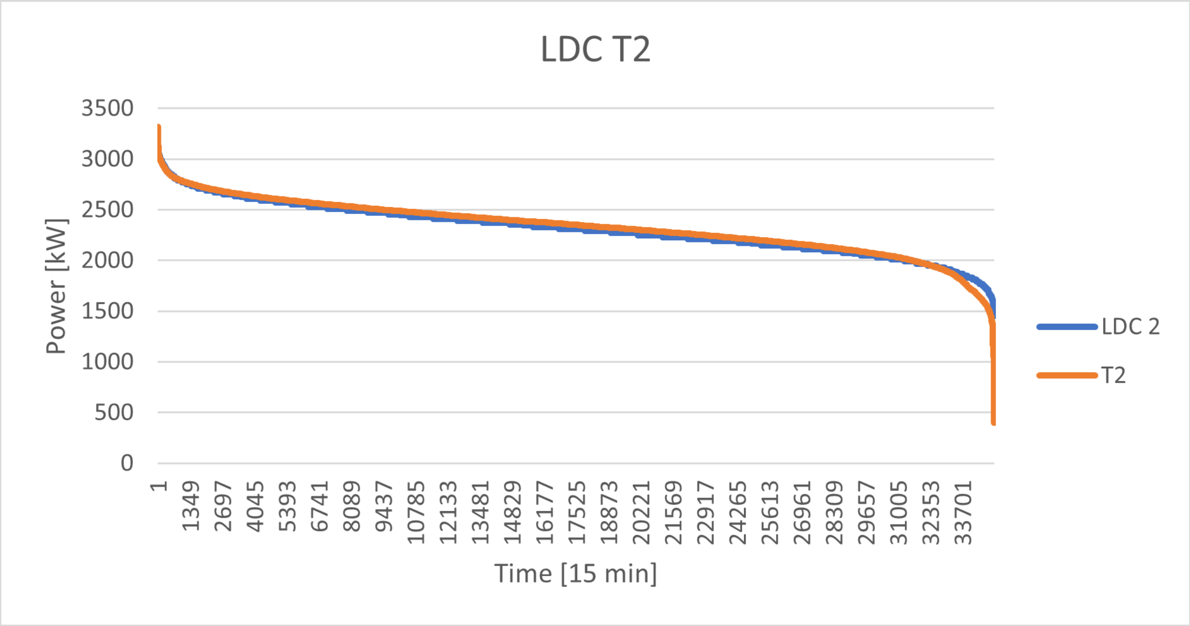


Figure D.2: Load duration curve of measured and generated load for terminal 2

Table D.2: Analysis on similarity between both profiles for terminal 2

Metric	Measured load	Generated load	Difference
Mean	2333	2309	1.05%
Median	2352	2310	1.79%
Std dev	270.4	250.1	7.50%
Skewness	-0.6793	0.0145	

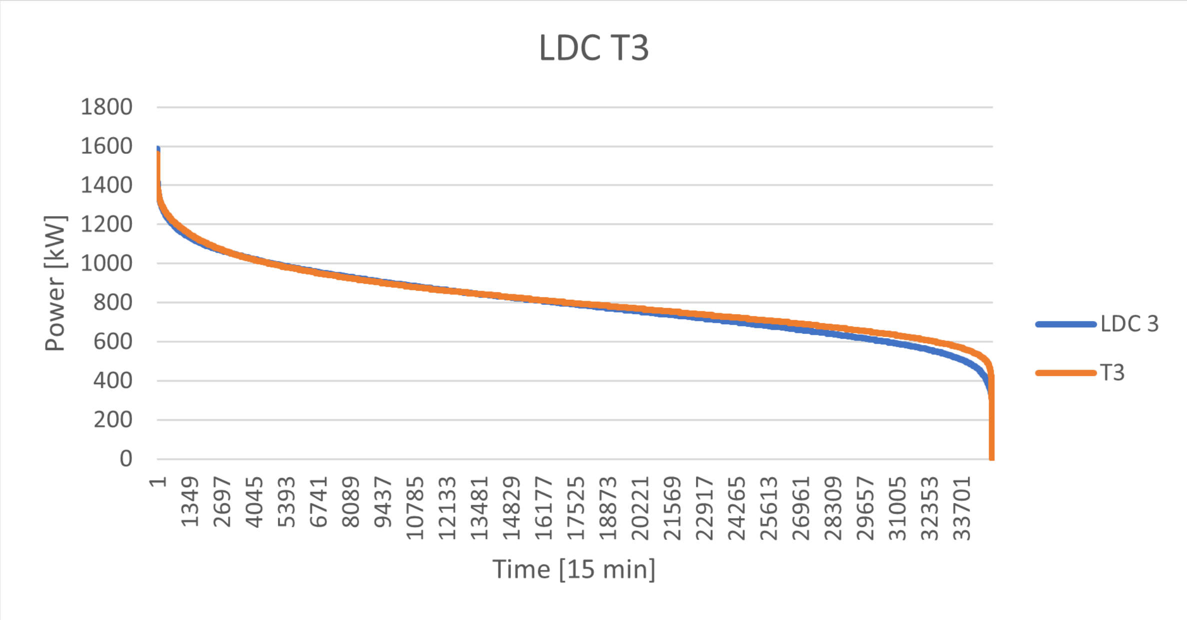


Figure D.3: Load duration curve of measured and generated load for terminal 3

Table D.3: Analysis on similarity between both profiles for terminal 3

Metric	Measured load	Generated load	Difference
Mean	816	800	1.92%
Median	796	791	0.63%
Std dev	166	180	8.46%
Skewness	0.456	0.284	

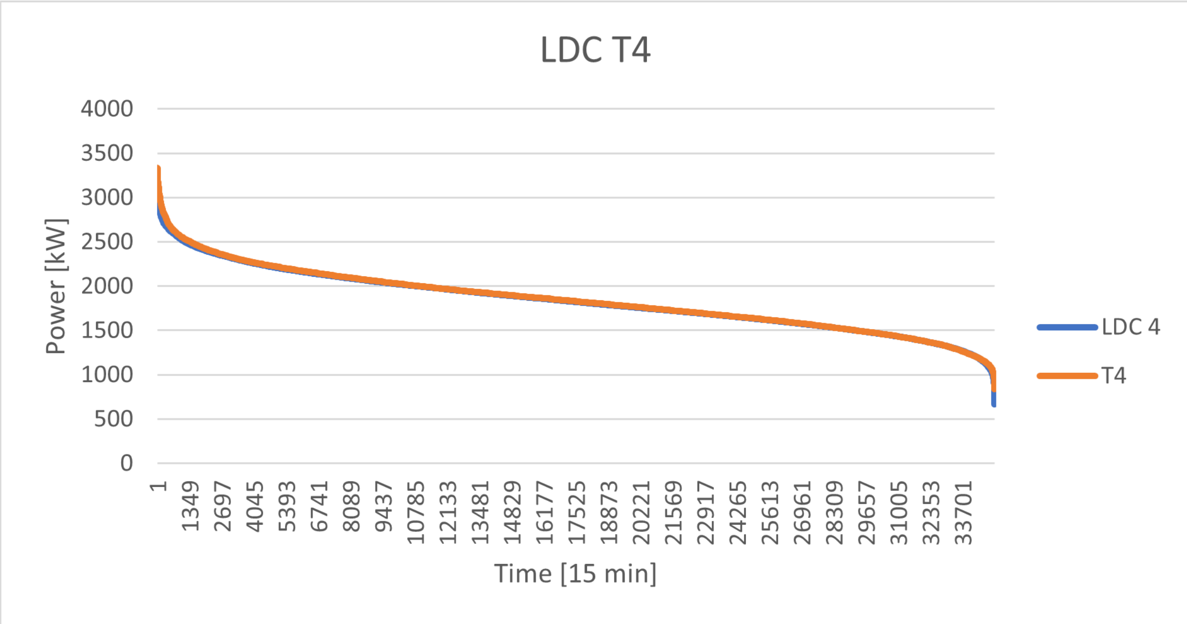


Figure D.4: Load duration curve of measured and generated load for terminal 4

Table D.4: Analysis on similarity between both profiles for terminal 4

Metric	Measured load	Generated load	Difference
Mean	1847	1838	0.46%
Median	1828	1823	0.28%
Std dev	350.7	342.4	2.38%
Skewness	0.3738	0.2455	

E

Internal and external factors

For the design of the scenario space a literature search is performed. Reports describing future scenarios guided the development of a list of external and external factors and their parametrisation as well as quantification. The future scenarios described in business reports acted as directive for the bandwidths of the uncertainty intervals in the scenario model.

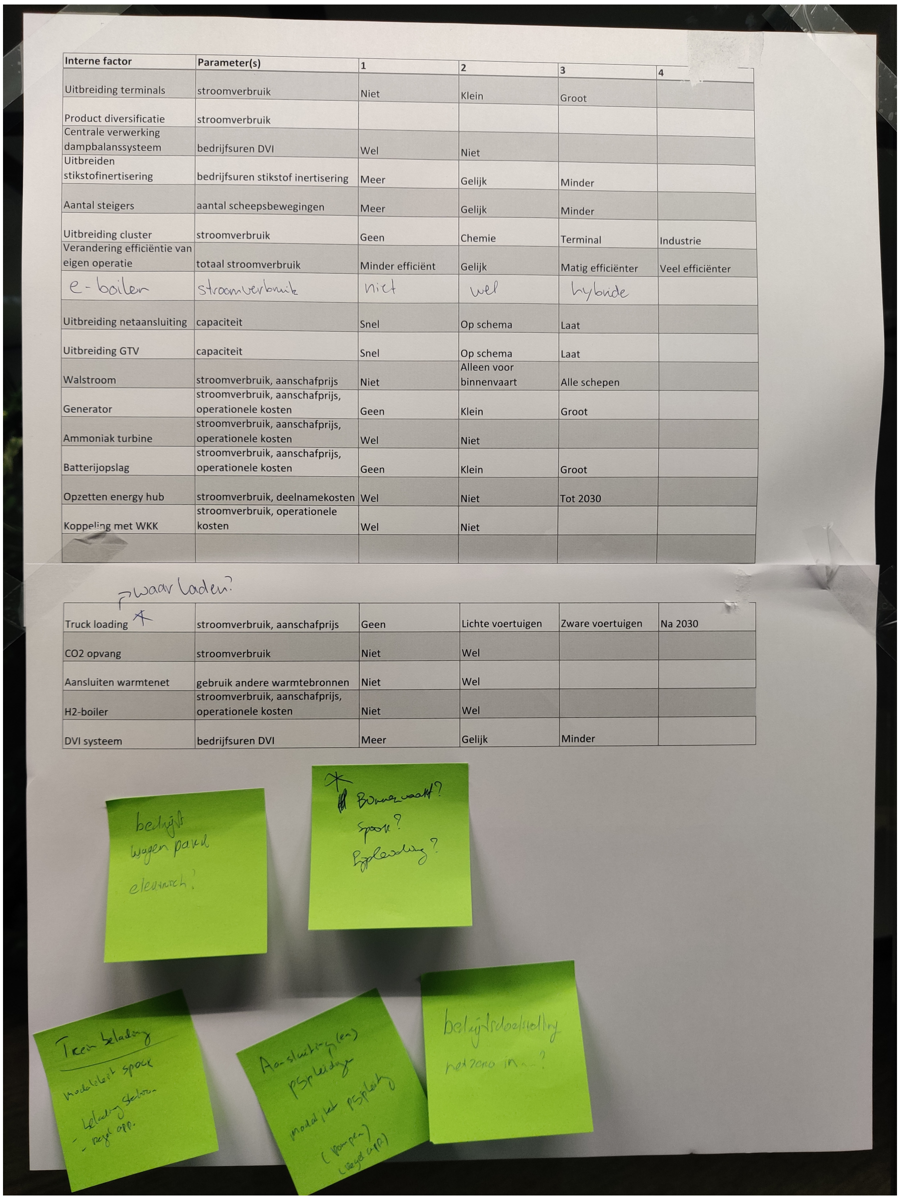
The outcomes of this literature search are presented in the form of an Excel sheet in Figures E.1 and E.2. In addition to a literature search two workshop sessions are organised to refine the lists of external and internal factors, as well as their parametrisation and quantification. The body of the workshop sessions was a brainstorm on the different factors. Participants were asked to write down internal and external factors they could think of that might impact the cluster of terminals in the future. An image is presented in Figure E.3 and Figure E.4 showing parts of the outcomes of the workshop. In the following part of the workshop factors already on the list or newly written down were discussed.

	Lever	Parameter(s)	1	2	3	4	Kolom1	12	23	34	45
1	Walstroom	Pb, Pm, Pp	Niet	Alleen vo	Alle schepen						
2	Installatie generator	Pb, Pm, Pp	Geen	Klein	Groot						
3	Installatie ammoniak turbine	Pb, Pm, Pp	Wel	Niet							
4	Batterijopslag	Pb, Pm, Pp	Geen	Klein	Groot						
5	Uitbreiding netaansluiting	capaciteit	2027	2029	2031						
6	Uitbreiding terminals	Pb, Pm, Pp	Niet	Klein	Groot						
7	Product diversificatie	Pm, Pp									
8	Opzetten energy hub	Pb, Pm, Pp	Wel	Niet	Tot 2030						
9	Koppeling met WKK	Pb, Pm, Pp	Wel	Niet							
10	Centrale DVI	bedrijfsuren DVI	Wel	Niet							
11	DVI systeem	bedrijfsuren DVI	Meer	Gelijk	Minder						
12	Uitbreiden stikstofinertisering	bedrijfsuren stiks	Meer	Gelijk	Minder						
13	Aanpassing tankdaken										
14	Aantal steigers	berths	Meer	Minder							
15	Uitbreiding cluster		Geen	Chemie	Terminal	Industrie					
16	Installatie truck loading		Geen	Lichte voe	Zware voe	Na 2030					
17	Installatie CO2 opvang		Niet	Wel				-	CO2 pomp + CO2 tank		
18	Aansluiten warmtenet		Niet	Wel							
19	Ontwikkeling H2-boiler										
20	Verandering efficiëntie van eigen operatie		-1% per ja	0% per jaa	1% per jaa	2% per jaar		-1% per ja	0% per jaa	1% per jaa	2% per jaar
21	Treinvervoer	Pb, Pm, Pp	Minder	Gelijk	Meer						
22	Truckvervoer	Pb, Pm, Pp	Minder	Gelijk	Meer						
23	Pijpleidingvervoer	Pb, Pm, Pp	Minder	Gelijk	Meer						
24	Binnenvaartvervoer	Pb, Pm, Pp	Minder	Gelijk	Meer						
25	Beleidsdoelstelling terminal o	(L)									
26	Elektrisch wagenpark	Pb, Pm, Pp	wel	niet							
27	E-boiler	Pb, Pm, Pp	wel	niet							

Figure E.1: Outcome of the literature search on internal factors

Nr	Categorie	Externe factor	Parameter(s)	Bron	1	2	3	4	5	S1	S2	S3	S4	S5	Unit
1	Haven	Verandering aantal scheepsbewegingen	Berths, pumps, nieuwe assets	HbR 2050	Connected Deep Green	Wake-Up Call	Protective Markets	Regional Well-being		-34%	-35%	-29%	-43%		(2050 tov 2020)
2	Haven	Overslag kamertemperatuur	Berths, pumps, nieuwe assets	HbR 2050	Connected Deep Green	Wake-Up Call	Protective Markets	Regional Well-being		32%	16%	13%	28%		(% in 2050)
3	Haven	Overslag koelproduct	Berths, pumps, nieuwe assets	HbR 2050	Connected Deep Green	Wake-Up Call	Protective Markets	Regional Well-being		4.70%	2.70%	2.80%	2.30%		(% in 2050)
4	Haven	Overslag cryogeenproduct	Berths, pumps, nieuwe assets	HbR 2050	Connected Deep Green	Wake-Up Call	Protective Markets	Regional Well-being		13.50%	13.10%	0%	21.60%		(% in 2050)
5	Haven	Overslag Mineral oil products		HbR 2050	Connected Deep Green	Wake-Up Call	Protective Markets	Regional Well-being		0%	-63%	-38%	-73%		(2050 tov 2020)
6	Haven	Overslag fossiele brandstof HIC		SmartPort /	Connected Deep Green	Wake-Up Call	Protective Markets	Regional Well-being		-100%	-87%	-67%	-100%		(2050 tov 2020)
7	Haven	Aanleg walstroom	Walstroom		Snel	Voor 2050	Na 2050			2030	2035	2040	2045		2050
8	Wet- en regelgeving	Duur vergunningsprocedure	installatietijd												
9	Haven	Uitrol landelijk waterstofnet HIC-deel	prijs H2	Routekaart,	nMIEK					2025					
10	Wereld	Ontwikkeling H2-prijs	prijs H2	WEC	Laag	Midden	Hoog			200	100	50			(€/MWh)
11	Energiemarkt	Volatiliteit gasprijs	midprijs gas, piekprijs gas												
12	Energiemarkt	Ontwikkeling gasprijs	T prijs gas	Klimaatakk	PBL	IEA (EU) low	KEV	CE Delft 'lage / hoge prijzen'	Aurora	18-24 18-	18-34	24-51	22-46	21 (2030)	(€/MWh)
13	Energiemarkt	CO2-prijs / EU ETS	Verhoogde operationele kosten ge	H-vision/IEA	Low	Mid	High			17-44	17-100	17-149	15-40 (20	7-25 €/tor	(€/ton CO2)
14	Haven	Ontwikkeling CCS	prijsT gas (L)	Energiemix	Mogelijkheid CO2 opslag	Geen mogelijkheid				2030	2040	2050			
15	Haven	Uitfaseren WKK	switch (L)	Routekaart,	Volledige afbouw	Ombouw naar bio	Flexcapaciteit			Uitgefas	" in 2040	" in 2050	Omgebo	Omgebouwd naar biomassa	
16	Energiemarkt	Aanschafkosten van batterij	CAPEX, OPEX	CE Delft Om	CE Delft	IRENA				152 k€/M	700 €/kW	200 €/kW	175-185 $/kWh		(in 2030)
17	Energiemarkt	Aanschafkosten van generator	CAPEX, OPEX												
18	Haven	Batterijcapaciteit HIC	prijs elec, afschakeling industrie	II3050 (flex I	Normaal	-33%	-66%	Geen		0%	-58%	-75%	-97%		(tov normaal)
19	Netbeheerders	Gevraagde DSR	afschakeling capaciteit (mixers)	II3050	DEC	NAT	EUR	INT		3%	5%	7%	7%		
20	Wet- en regelgeving	Energiebesparingsplicht			<5 jaar ROI										
21	Energiemarkt	Kosten CCS	prijs CCS												
22	Wet- en regelgeving	Strengere veiligheidsapparatuur	stroomverbruik	DCMR (PGS 29/12)											
23	Energiemarkt	Volatiliteit elektriciteitsprijs	midprijs elec, piekprijs elec, LDC el	DNV GL	Gelijk (mix/bio/fossiel)	Hoger									
24	Energiemarkt	Kosten elektriciteit	T prijs elektriciteit	PBL, CE Delft	PBL	Strategy&	PBL	CE Delft 'lage/hoge prijzen'	CE Delft s	150 €/MV	122 €/MV	47 €/MW	50-93 €/N	60.6-101.4	67-115 €/MWh (2030) 90-105 €/MWh (2050)
25	Netbeheerders	non-firm ATO?	aansluitprijs, prijs elec	LAN											
26	Netbeheerders	Aanpassing nettariefstructuur, kWflex / I	prijsp, prijsb elec	LAN											
27	Netbeheerders	congestiecharge?	prijsp elec	LAN											
28	Wet- en regelgeving	Extra subsidievoorwaarden opslag	subsidie batterij/PV	LAN											
29	Netbeheerders	Snelheid uitbreiding elektriciteitsnet	Terugverdientijd	II 2030-2050	II3050/nMIEK	CES				2028	2026				
30	Haven	Groei elektriciteitsvraag HIC -> nieuwe c	Kortere terugverdientijd												
31	NL	Interconnectie met buurlanden	prijs elec	II3050	Verwacht	Laag	Geen			-2%	1%	10%			
32	Haven	Mogelijkheid aansluiten warmtenet	prijsT gas												
33	Terminal	Waterstof voor verwarming	prijsT gas, (L) H2-boiler	Energiemix											
34	Terminal	Ontwikkeling elektrische fornuizen	prijsp elec, (L) e-boiler	Energiemix,	Routekaart										
35	Wet- en regelgeving	SDE++ op elektrificatietechnieken	Aanschaf / operationele kosten	Routekaart											
36	Wet- en regelgeving	Subsidies energiehubs													
37	Wet- en regelgeving	Subsidies op batterij													

Figure E.2: Outcome of the literature search on external factors



Interne factor	Parameter(s)	1	2	3	4
Uitbreiding terminals	stroomverbruik	Niet	Klein	Groot	
Product diversificatie	stroomverbruik				
Centrale verwerking dampbalanssysteem	bedrijfsuren DVI	Wel	Niet		
Uitbreiden stikstofinertisering	bedrijfsuren stikstof inertisering	Meer	Gelijk	Minder	
Aantal steigers	aantal scheepsbewegingen	Meer	Gelijk	Minder	
Uitbreiding cluster	stroomverbruik	Geen	Chemie	Terminal	Industrie
Verandering efficiëntie van eigen operatie	totaal stroomverbruik	Minder efficiënt	Gelijk	Matig efficiënter	Veel efficiënter
e-boiler	stroomverbruik	niet	wel	hybride	
Uitbreiding netaansluiting	capaciteit	Snel	Op schema	Laat	
Uitbreiding GTV	capaciteit	Snel	Op schema	Laat	
Walstroom	stroomverbruik, aanschafprijs	Niet	Alleen voor binnenvaart	Alle schepen	
Generator	stroomverbruik, aanschafprijs, operationele kosten	Geen	Klein	Groot	
Ammoniak turbine	stroomverbruik, aanschafprijs, operationele kosten	Wel	Niet		
Batterijopslag	stroomverbruik, aanschafprijs, operationele kosten	Geen	Klein	Groot	
Opzetten energy hub	stroomverbruik, deelnamekosten	Wel	Niet	Tot 2030	
Koppeling met WKK	stroomverbruik, operationele kosten	Wel	Niet		
Truck loading	stroomverbruik, aanschafprijs	Geen	Lichte voertuigen	Zware voertuigen	Na 2030
CO2 opvang	stroomverbruik	Niet	Wel		
Aansluiten warmtenet	gebruik andere warmtebronnen	Niet	Wel		
H2-boiler	stroomverbruik, aanschafprijs, operationele kosten	Niet	Wel		
DVI systeem	bedrijfsuren DVI	Meer	Gelijk	Minder	

Figure E.3: Image of part of the outcomes of the brainstorm during the workshop

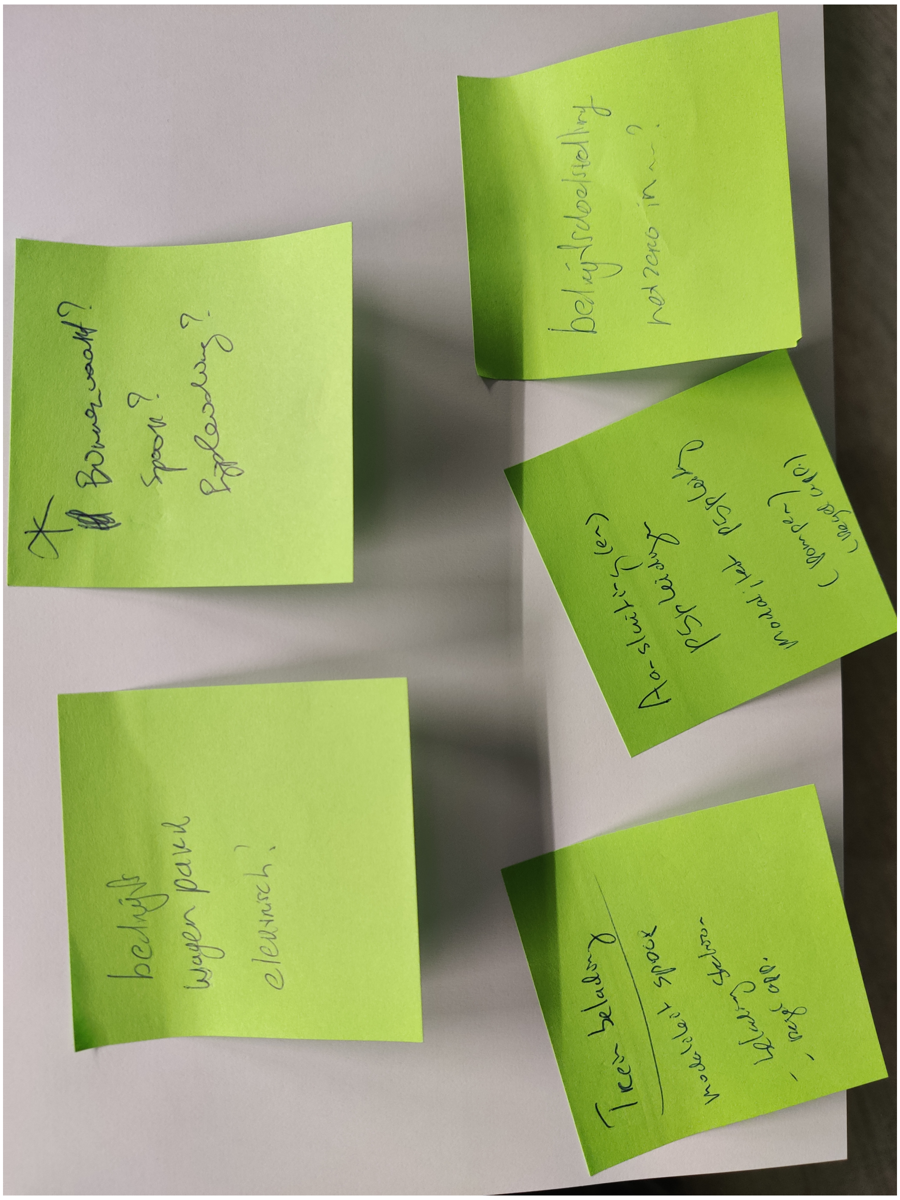


Figure E.4: Image of provided internal factors as preparation for the workshop, additional factors are written down and pasted on the list

F
Modelling assumptions

Nr.	Source	Paremeter	Assumptions
1	Terminal ope	Flex capacity	No flex capacity is available at the terminal. All flexibility comes from added assets
2		n	all component amounts are chosen based on component amounts for a general terminal in the HIC
3		P	all power ratings are chosen so that they are not indicative for the measured data profile, yet still representative for terminal operation
4		num_interval:	the first week of the year is used for generating the load profile for which the overload is calculated, this is long enough to generate a representative profile while minimising computational effort
5	PoR	P_CHP	When connecting an electricity generation unit must be assumed that a battery needs to be installed in order to balance the inertia (15 min ramping) of the system. However, since a 15-min period is chosen this is no longer relevant
6	PoR	P_shore	Currently no shore power for liquid bulk vessels
7	CE Delft	P_shore	Bulk terminal vessel requires 500kW
8	Terminal ope	P_shore	350kW barge, 2600kW SGV
9	Lit search	P_shore	Shore power will be used for both the hotel function as wel as unloading
10	PoR	P_shore	Shore power will be able to facilitate unloading in the future (currently not allowed due to ATEX)
11	Lit search	n_shore	Shore power will be installed at 20% capacity or full, denoted by 1 and 2 respectively in the code
12	PoR	P_pumps	Pumps only used while loading, unloading is done by pumps on-board (not for shore power scenario)
13	Lit search	t_loading, t_u	1/5 loading, 4/5 unloading
14	Terminal ope	P_nitrob, geb	SGV uses 200, barge then uses 200/5/48*38=32kW
15	Lit search	GTV, RDF	In an industrial context a rated diversity/coincidence factor of 0.9 is assumed. Group-contract will be 10-30% lower than aggregated GTV
16	PoR	Truck chargir	Charging takes place during loading
17	Lit search	Truck chargir	Trucks are loaded only between 08:00-18:00
18	Lit search	Truck chargir	Loading up a truck takes 30 min
19	Lit search	Truck chargir	The time where truck loading station is vacant varies between 0 min and 2h
20		EV charging	Half of employees at terminal work in 8h shifts, other half 8-4
21		EV charging	Employees working in shifts perfectly overlap eachother, employees working 9-5 hours are at the office for 7-9 hours
22	Terminal ope	berths, EV/tru	Terminals operate 24/7
23	Terminal ope	compressors	Compressors operate at random intervals throughout the day to circulate products and keep the system within preferred operating limits
24	Terminal ope	DVI	DVI's operate at random intervals throughout the day to recover vapours that originate in the tanks
25	Lit search	n_nitrob	For both barges and SGVs 1/6 ships requires nitrogen blanketing
26	Lit search	n_Eboiler	During winter, the e-boiler has a utilization rate of 0.75, during spring and autumn 0.5 and during summer 0.25
27	Lit search	P_Eboiler	20MW for big installation covering all heat demand, 10MW for small installation covering partial heat demand
28	Lit search	berths barge/	average berth time barge/SGV: 38/48hrs
29	Data analysis	P_elec	combined measured GTV is 12,000kW, assumed GTV for 2 or 3 terminals is 15,000kW for 4 terminals 20,000kW
30		P_elec	when flex capacity is found in the HIC before 'Loadpocket Simonshaven' is completed it is assumed additional capacity can be provided of 5000kW
31	Lit search	P_elec	grid capacity increases to 40,000kW after completion of 'Loadpocket Simonshaven'. This is approximately 2,5x the current estimated GTV (15,000kW)
32	Lit search	n_EV	estimated at 10, 50, 25, 20 Evs based on terminal size. Partial electric car park would be 20%
33	Lit search	n_truck	estimated at 3,10,8,10 trucks based on terminal size. Partial electric car park would be 1,2,2,2
34	Lit search	n_DVIs	maximum amount of DVIs estimated at 2,10,8,10 based on terminal capacity
35	Terminal ope	P_DVIs	between 200 and 600 kW. 25% in use
36	Lit search	n_comp	minimum of 2, 10, 8, 10; maximum of 8, 40, 32, 40 based on terminal capacity
37	Terminal ope	P_comp	20kW
38	Lit search	n_mixers	mixers operate 2x 16 hours per month
39	Lit search	n_mixers	min: 5, 150, 150, 50; max: 20, 500, 550, 200 based on amount of tanks. Assuming every tank is equipped with a mixer installation. Every mixer runs for 16hrs every month
40	Lit search	n_SGV	min: 0, 2, 1, 2; max: 3, 8, 5, 7 based on current spots. Potential expansion possibilities taken into account
41	Lit search	lb/ub_SGV	real berth data is extrapolated to generate a representative berthing schedule
42	Terminal ope	P_pump_SG	1000 kW
43	Lit search	n_barge	min: 2, 8, 5, 10; max: 4, 20, 15, 20 based on average spots. Potential expansion possibilities taken into account
44	Lit search	lb/ub_barge	real berth data is extrapolated to generate a representative berthing schedule
45	Data analysis	P_other	0-200 kW every 15 mins (avg 100kW). Based on fit with actual electricity demand profile data. Can increase to 1000kW (avg 500kW)
46	Data analysis	P_other	tank heating requires continuous electricity for the ancillary infrastructure of the gas boiler. Assumed 25kW semi-continuous (averaged at 25 kW fluctuating every 15 mins
47	Terminal ope	P_max_load	During yearly peak load there is no flex capacity available to mitigate the peak
48	Lit search	P_Eboiler	Potential heat pump installation is assumed to have equal capacity as 10MW boiler. (COP of 4 makes 4MW heat pump)
49	PoR	P_Eboiler	Potential electrical tracing installation will require similar electricity demand as an e-boiler as it is applied for equal use
50	Lit search	P_Eboiler	Heat demand of single tank is 50kW. On average the terminal has 800 tanks installed. Assuming at most half of the tanks need to be heated a heating demand of 20MW is required
51	Empirical	P_Eboiler	an e-boiler can operate at 20 different modes to supply the required heat
52	Lit search	P_lighting	Assumed to be negligible, as calculations resulted in a power demand of 1kW
53	Lit search	P_wind	Wind turbine that would be placed would be of the same model as already in operation at the Slufterdam - Vestas V112-3.45
54	Lit search	P_wind	Cut-off speed of Vestas V112-3.45 is 25 m/s, this is however not measured in the reference year that is used for the wind power calculation
55	PoR	n_wind	Due to area restrictions a maximum of 2 wind turbines could be placed
56	PoR	P_solar	The potential area of solar panels is assumed on representative terminals in ports. Small parameter is for the case where only office roofs can be used, larger area is for if solar panels can potentially be installed on top of storage tanks
57	Lit search	P_gen	a generator set can be installed in two sizes, 1000kW and 5000kW
58	Lit search	P_bat	a BESS can be installed in two sizes, 1000kW and 5000kW

Figure F.1: Overview of all assumptions made in the construction of both models, presented in an Excel sheet

G
Sensitivity Analysis

A sensitivity analysis is done to verify the outcomes of the simulation model and PRIM analysis. The exact values of the outcomes in this research are less important than the story they tell. As described in Chapter 10, the model lacks detail to use the outcomes for calculations on system planning. The outcomes do however illustrate important drivers in the development of the cluster's energy system. This sensitivity analysis is done to show the model is implemented correctly and subsequent analyses are sound. First, the outcomes of the simulation model are tested when calculated for different initial parameters. Then, the outcomes for the PRIM analysis are compared to outcomes for similar but different scenario simulations.

G.1. Simulation model

As explained in Chapter 8 the simulation model calculates the operating schedules of the components at the start of a run. This means that for every generated scenario the same schedule is used. Depending on the configuration of the energy hub for every single scenario the profile then differs. An example of some profiles generated from the same schedule is shown in Figure G.1.

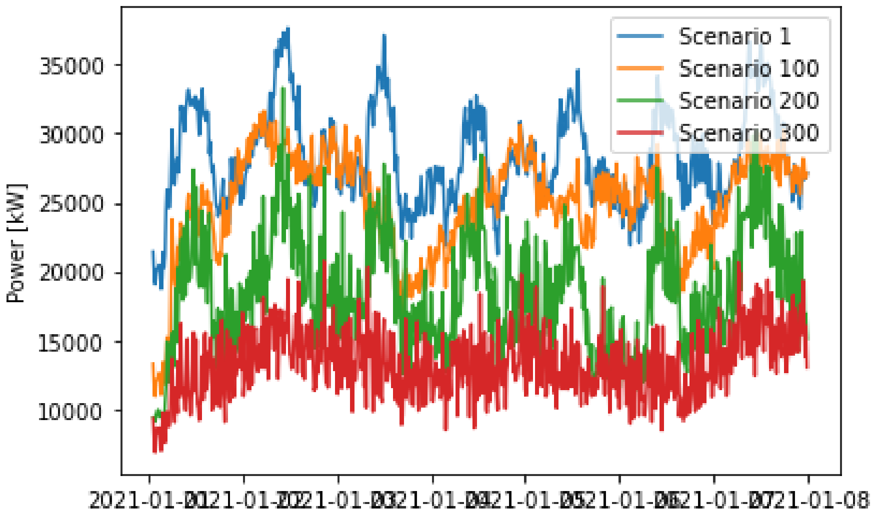


Figure G.1: Load profiles for various simulation runs

The figure shows the load profiles of the cluster as a consequence of differing configurations. The configurations are subsequently determined by the parameters chosen for every single scenario. From the figure can be seen that even though the same schedule is used to generate the load profiles, different profiles are generated. Nevertheless, it is interesting to evaluate the effect of a different schedule, as base for the simulations. Another simulation is run that uses a different generated schedule, but equal parameter ranges. The run is performed for 20 scenarios and 400 policies as well. The outcome of the feature scoring shows the parameters influencing the overloads for this simulation run in Table G.1. When comparing this feature scoring to the one in 9.1 it is clear that similar results are obtained. Both tables show a similar outcome as 'P_{elec}' and '$shore_{SGV}$' top the table followed by '$P_{Eboiler}$', 'P_{CHP}' and '$n_{terminals}$'. At the bottom of the table variables associated with the area of solar PV, EV charging or VRU's are found. The tables do show however that the variables are not weighted exactly similar. Nonetheless, similar conclusions can be drawn on components influencing the overload of the system.

Table G.1: Top and bottom 10 feature scores of another simulation run for 'overload'

Nr	Parameter	Score	Nr	Parameter	Score
1	P_elec	0.2184	34	n4_SGV	0.0051
2	shore_SGV	0.1942	35	n1_mixers	0.0050
3	P_CHP	0.1287	36	A4_solarPV	0.0050
4	P_Eboiler	0.1139	37	n3_DVI	0.0049
5	n_terminals	0.0555	38	A2_solarPV	0.0049
6	n2_SGV	0.0293	39	n3_comp	0.0049
7	shore_barge	0.0196	40	n4_EV	0.0048
8	n2_barge	0.0130	41	n3_barge	0.0047
9	n1_SGV	0.0126	42	n3_EV	0.0045
10	n1_truck	0.0113	43	A1_solarPV	0.0045

For these simulations it was chosen to calculate 8000 experiments, as 20 scenarios and 400 policies are selected. In Tables G.2 and G.3 the feature scoring is shown following simulation runs with 100 scenarios/400 policies and 20 scenarios/2000 policies respectively. Both thus calculate 40,000 experiments. This is close to the largest possible set of experiments that could be computed using the available hardware, as a set of 50,000 experiments could not be computed.

Table G.2: Top and bottom 10 feature scores of simulation run for 'overload' using 100 scenarios/400 policies

Nr	Parameter	Score	Nr	Parameter	Score
1	P_elec	0.2234	34	n_wind	0.0059
2	shore_SGV	0.1820	35	A3_solarPV	0.0057
3	P_Eboiler	0.1296	36	A4_solarPV	0.0057
4	P_CHP	0.0902	37	A1_solarPV	0.0057
5	n_terminals	0.0680	38	P_DVI	0.0057
6	n2_SGV	0.0231	39	n2_comp	0.0057
7	P_gen	0.0142	40	n3_EV	0.0054
8	shore_barge	0.0133	41	n3_DVI	0.0054
9	P_bat	0.0131	42	n3_truck	0.0051
10	n3_SGV	0.0121	43	n1_DVI	0.0050

Both tables again show similar outcomes for the feature scoring for different simulation runs. For the simulation run with 20 scenarios and 2000 policies the most influential variable is now '$shore_{SGV}$'. Nevertheless, 'P_{elec}' is still second with both showing similar values. The power rating of e-boilers and the CHP-system are again the third and fourth variable, followed by the amount of terminals interconnected in the cluster.

G.2. PRIM

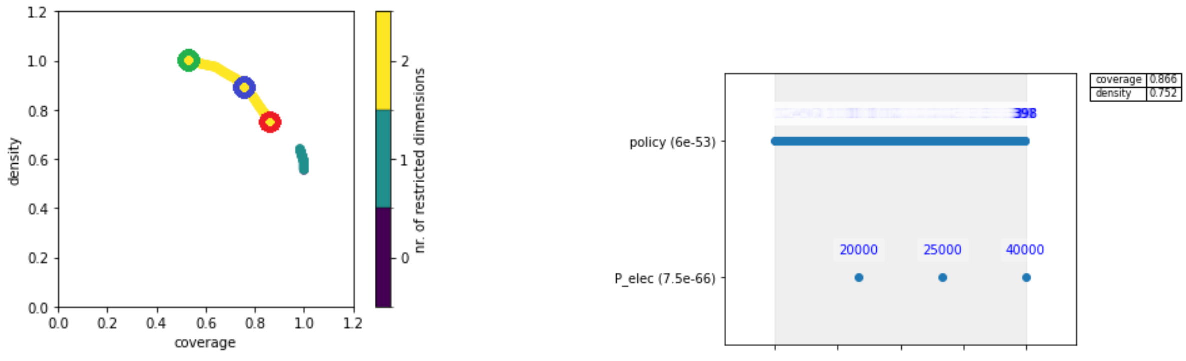
A similar analysis is done on the outcomes of the PRIM analysis. First, for a single simulation run the outcomes of different PRIM-boxes is compared. Then, the effect on the outcomes is evaluated when a different simulation run is used to generate PRIM-boxes.

First, different PRIM-boxes are evaluated from the same simulation run. Figure G.2a shows the tradeoff plot for the used simulation run. In this plot Box 60 is indicated by the red circle, Box 150 by the blue

Table G.3: Top and bottom 10 feature scores of simulation run for 'overload' using 20 scenarios/2000 policies

Nr	Parameter	Score	Nr	Parameter	Score
1	shore_SGV	0.2184	34	n1_comp	0.0037
2	P_elec	0.1902	35	n2_DVI	0.0037
3	P_Eboiler	0.1404	36	n2_mixers	0.0037
4	P_CHP	0.1395	37	A1_solarPV	0.0037
5	n_terminals	0.0409	38	n3_truck	0.0036
6	n2_SGV	0.0403	39	n3_DVI	0.0036
7	shore_barge	0.0267	40	n1_DVI	0.0036
8	n3_SGV	0.0149	41	n4_SGV	0.0036
9	n1_SGV	0.0146	42	n3_mixers	0.0035
10	P_gen	0.0141	43	n4_DVI	0.0035

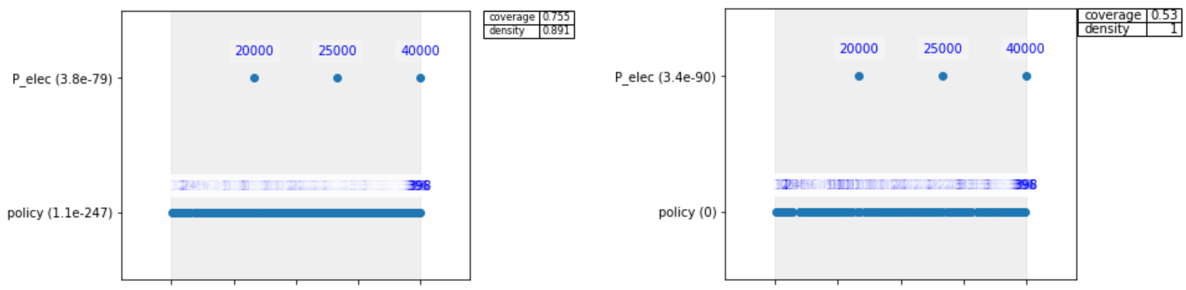
circle and Box 244 by the green circle. The output of the PRIM-boxes shows that all generate the same outcome. During the course of this research there have been instances where different PRIM-boxes with the same number of restricted dimensions have produced different outcomes. Therefore, the goal has been to chose the PRIM-box with the highest score for both density and coverage while having three or four restricted dimensions, as described in Chapter 8.



(a) Plot showing tradeoff, Box 60 (red), Box 150 (blue), Box 244(green)

(b) Details of chosen box: Box 60

Figure G.2: PRIM-boxes for overloads = 0



(a) Details of chosen box: Box 150

(b) Details of chosen box: Box 244

Figure G.3: PRIM-boxes for overloads = 0

When plotting the tradeoff for a different simulation run with equal initial parameters a similar curve is the result, as is shown in Figure G.4. Furthermore, the outcome for the PRIM-boxes of this simulation is equal to the PRIM-boxes found for the previous simulation run. PRIM-box 150 is indicated by the red circle in Figure G.4. These analyses show that the results provided in Chapter 9 are sound and conclusions can be drawn on the outcomes of the simulations.

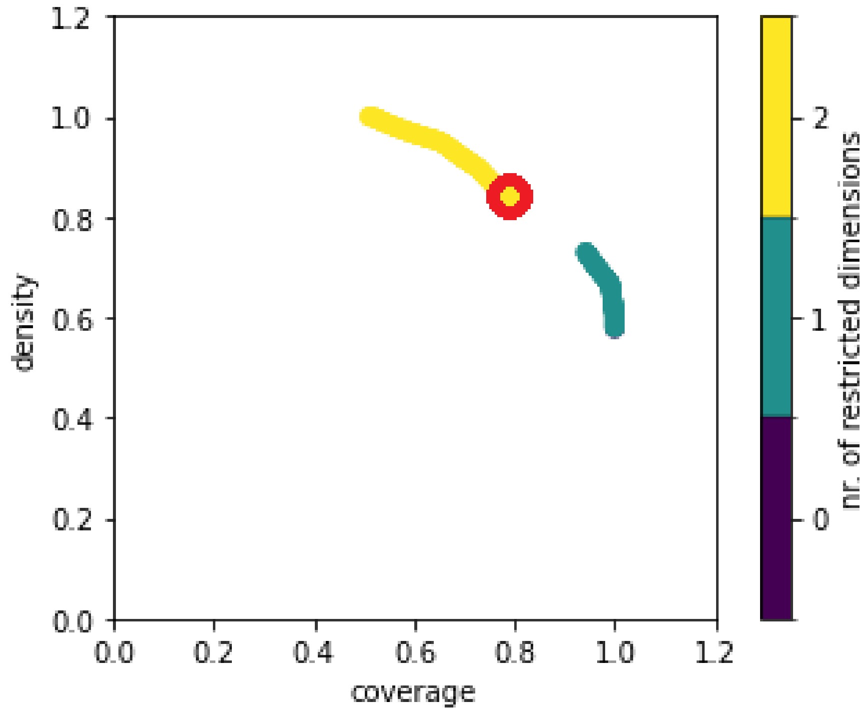


Figure G.4: Plot showing tradeoff for different simulation run

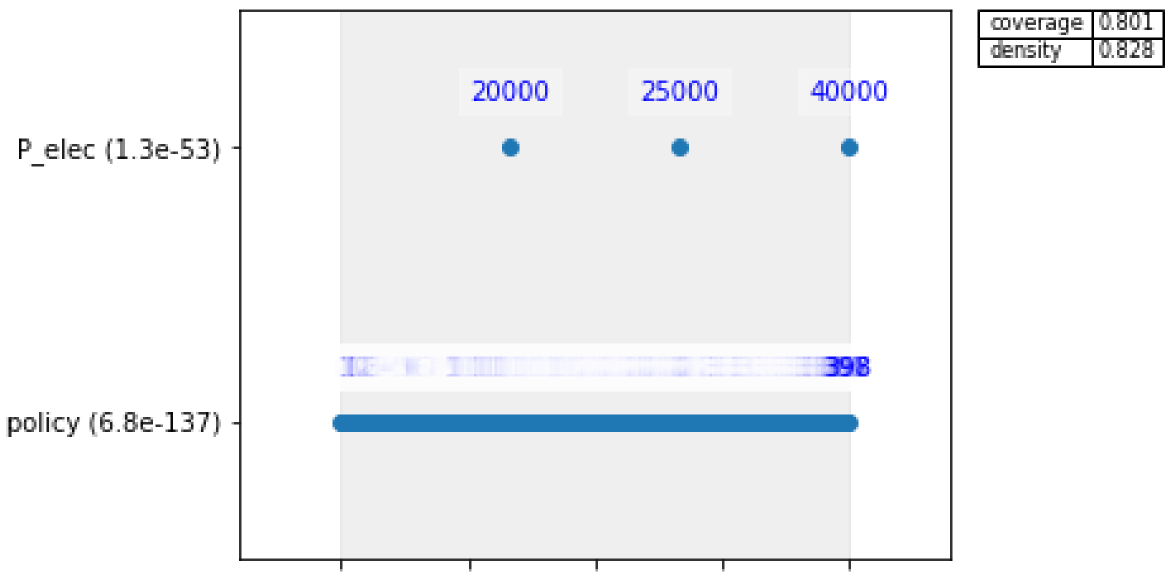


Figure G.5: Details of chosen box: Box 103

H

Python Code

```
# -*- coding: utf-8 -*-
"""
Created on Tue Mar 19 11:35:21 2024

@author: lbal1
"""

import sys
import random
import copy
import numpy as np
import pandas as pd
import matplotlib.pyplot as plt
from ema_workbench import Model, Constant, RealParameter, BooleanParameter, IntegerParameter,
     CategoricalParameter, ArrayOutcome, ScalarOutcome, ema_logging, perform_experiments
from ema_workbench.util.utilities import save_results, load_results
from ema_workbench.analysis.scenario_discovery_util import RuleInductionType
import ema_workbench.analysis.prim as prim

from ema_workbench.analysis import feature_scoring
import seaborn as sns
ema_logging.log_to_stderr(ema_logging.INFO)

#%% Import datasets

irradiation = pd.read_excel("zonuren_2021_Rotterdam.xlsx", usecols='AA', skiprows
    =[0,1,2,3,4,5,6,7,8])
wind_speed = pd.read_excel("windsnelheden_2021_Rotterdam.xlsx", usecols='Z', skiprows=range
    (11))

#%% Scenario parameters
P_mixer  = 40
mixer_utilisation = [(32/730), ((714)/730)]
P_comp   = 20       # compressor power
P_nitrob_barge = 40
P_nitrob_SGV   = 200
P_truck = 400
P_EV = 55                                                                # Suffices for
     regular charging throughout the day
num_modes_Eboiler = 20                                                   # 2 * 20 times
     25 or 100 = 1 or 4 MW E-boiler

num_intervals_per_year = 672 # first week

#%% Variable generation
# Solar PV
P_solarPV = 0.0002 * irradiation                                         # 20%
    efficiency - P in [kW/m2]
P_solarPV = P_solarPV[:num_intervals_per_year]
```

```python

# Wind - Vestas V112-3.45
V = wind_speed
V[V < 3] = 0
V[V > 13] = 13
# cut-off speed van turbine is 25 m/s
Cp_wind = 0.817536
rho_air = 1.225                                                          # density [kg/m^3]
blade_radius = 56

wind_power = 0.0005 * Cp_wind * rho_air * blade_radius**2 * V**3             # Wind power in kW  - 1/2*Cp*rho*R^2*V^3
P_wind = wind_power[:num_intervals_per_year]
#%% Barge pumps+shorepower
# Barge berths STR - gem. 151 = 38 uur
lb0_barge = [26, 36, 36, 28, 40, 8]
ub0_barge = [140, 256, 168, 360, 360, 352]

biased_set0_barge = [num for num in range(lb0_barge[0], ub0_barge[0])] + [num for num in range(lb0_barge[1], ub0_barge[1])] + [num for num in range(lb0_barge[2], ub0_barge[2])] + [num for num in range(lb0_barge[3], ub0_barge[3])] + [num for num in range(lb0_barge[4], ub0_barge[4])] + [num for num in range(lb0_barge[5], ub0_barge[5])]

def generate_ones_barge(terminal_berths):
    return random.choices([6, 1], [0.2, 0.8]) * random.choice(terminal_berths)

def generate_zeros_barge():
    return [0] * random.randint(6, 108)

full_barge_schedule = []

for i in range(78):                                                       # 78 is maximum amount of barge berths in cluster
    barge_schedule = []  # Initialize data for each dataset
    while len(barge_schedule) < num_intervals_per_year:
        zeros_block = generate_zeros_barge()
        barge_schedule.extend(zeros_block)
        ones_block_barge = generate_ones_barge(biased_set0_barge)
        barge_schedule.extend(ones_block_barge)
    # Trim excess data if generated more than required
    barge_schedule = barge_schedule[:num_intervals_per_year]
    # Append the data to the list of datasets
    full_barge_schedule.append(barge_schedule)

part_barge_shore_schedule = copy.deepcopy(np.array(full_barge_schedule))

for row in range(len(part_barge_shore_schedule)):
    for x in range(len(part_barge_shore_schedule[row])):
        if (part_barge_shore_schedule[row][x] == 1 or part_barge_shore_schedule[row][x] == 6):
            if random.randint(1,5) == 1:
                part_barge_shore_schedule[row][x] = 350
            else:
                part_barge_shore_schedule[row][x] = part_barge_shore_schedule[row][x] * 50

full_barge_shore_schedule = copy.deepcopy(np.array(full_barge_schedule))

for row in range(len(full_barge_shore_schedule)):
    for x in range(len(full_barge_shore_schedule[row])):
        if (full_barge_shore_schedule[row][x] == 1 or full_barge_shore_schedule[row][x] == 6):
            full_barge_shore_schedule[row][x] = 350

#%% SGV pumps + shorepower
lb0_SGV = [32, 180, 108, 96, 22, 60]
ub0_SGV = [364, 296, 572, 152, 96, 340]

biased_set0_SGV = [num for num in range(lb0_SGV[0], ub0_SGV[0])] + [num for num in range(lb0_SGV[1], ub0_SGV[1])] + [num for num in range(lb0_SGV[2], ub0_SGV[2])] + [num for num in range(lb0_SGV[3], ub0_SGV[3])] + [num for num in range(lb0_SGV[4], ub0_SGV[4])] + [num
```

```
     for num in range(lb0_SGV[5], ub0_SGV[5])]

def generate_ones_SGV(terminal_berths):
    return random.choices([3, 1], [0.2, 0.8]) * random.choice(terminal_berths)

def generate_zeros_SGV():
    return [0] * random.randint(6, 108)

full_SGV_schedule = []

for i in range(23):                                                    # 23 is
    maximum amount of SGV berths in cluster
    SGV_schedule = []  # Initialize data for each dataset
    while len(SGV_schedule) < num_intervals_per_year:
        zeros_block_SGV = generate_zeros_SGV()
        SGV_schedule.extend(zeros_block_SGV)
        ones_block_SGV = generate_ones_SGV(biased_set0_SGV)
        SGV_schedule.extend(ones_block_SGV)
    SGV_schedule = SGV_schedule[:num_intervals_per_year]
    full_SGV_schedule.append(SGV_schedule)

part_SGV_shore_schedule = copy.deepcopy(np.array(full_SGV_schedule))

for row in range(len(part_SGV_shore_schedule)):
    for x in range(len(part_SGV_shore_schedule[row])):
        if (part_SGV_shore_schedule[row][x] == 1 or part_SGV_shore_schedule[row][x] == 3):
            if random.randint(1,5) == 1:
                part_SGV_shore_schedule[row][x] = 2600
            else:
                part_SGV_shore_schedule[row][x] = part_SGV_shore_schedule[row][x] * 300

full_SGV_shore_schedule = copy.deepcopy(np.array(full_SGV_schedule))

for row in range(len(full_SGV_shore_schedule)):
    for x in range(len(full_SGV_shore_schedule[row])):
        if (full_SGV_shore_schedule[row][x] == 1 or full_SGV_shore_schedule[row][x] == 3):
            full_SGV_shore_schedule[row][x] = 2600

#%% Compressors
uptime_comp   = 16      # in hours
downtime_comp = 40      # in hours

def generate_ones_comp():
    return [1] * random.randint(1, uptime_comp)

def generate_zeros_comp():
    return [0] * random.randint(1, downtime_comp)

comp_data = []

# Generate the data for each compressor
for i in range(118):
    comp = []  # Initialize data for each dataset

    # Repeat the process until 35040 values are generated
    while len(comp) < num_intervals_per_year:
        ones_block = generate_ones_comp()
        comp.extend(ones_block)

        zeros_block = generate_zeros_comp()
        comp.extend(zeros_block)
    comp = comp[:num_intervals_per_year]

    # Append the data to the list of datasets
    comp_data.append(comp)

comp_data = np.array(comp_data)
#%% DVIs / BoGs
def generate_ones_DVI():
    return [1] * random.randint(16, 19)

```

```
# Function to generate a block of zeros
def generate_zeros_DVI():
    return [0] * random.randint(16, 91)

# Initialize the list to store all datasets
full_DVI_schedules = []

# Generate the data for each DVI
for i in range(24):
    schedules = []
    while len(schedules) < num_intervals_per_year:
        ones_block = generate_ones_DVI()
        schedules.extend(ones_block)

        zeros_block = generate_zeros_DVI()
        schedules.extend(zeros_block)
    schedules = schedules[:num_intervals_per_year]
    full_DVI_schedules.append(schedules)

full_DVI_schedules = np.array(full_DVI_schedules)
#%% Nitrogen blanketing barge
# Function to select approximately 1/6 of the berths from the berthing schedule
def select_berths_barge(berths):
    selected_berths_barge = []
    for schedule in berths:
        selected_schedule = []
        for berth in schedule:
            if (berth == 1 or berth == 6) and random.randint(1, 6) == 1:  # Select
                approximately 1/6 of the berths
                selected_schedule.append(1)
            else:
                selected_schedule.append(0)
        selected_berths_barge.append(selected_schedule)
    return selected_berths_barge

full_barge_schedule = np.array(full_barge_schedule)

#%% Nitrogen blanketing SGV
# Function to select approximately 1/6 of the berths from the berthing schedule
def select_berths_SGV(berths):
    selected_berths_SGV = []
    for schedule in berths:
        selected_schedule = []
        for berth in schedule:
            if (berth == 1 or berth == 3) and random.randint(1, 6) == 1:  # Select
                approximately 1/6 of the berths
                selected_schedule.append(1)
            else:
                selected_schedule.append(0)
        selected_berths_SGV.append(selected_schedule)
    return selected_berths_SGV

full_barge_schedule = np.array(full_barge_schedule)
full_SGV_schedule = np.array(full_SGV_schedule)

#%% Truck charging
non_truck_t = 12# up to 3 hours of no truck

load_time = 2 # half an hour loading / charging

def generate_ones_truck():
    return [1] * load_time

def generate_zeros_truck():
    return [0] * random.randint(1,non_truck_t)

truck_schedule = []

for i in range(31):
    truck = []  # Initialize data for each dataset
    while len(truck) < num_intervals_per_year:
```

```
        # Generate a block of ones
        zeros_block = generate_zeros_truck()
        truck.extend(zeros_block)
        ones_block = generate_ones_truck()
        truck.extend(ones_block)

    truck = truck[:num_intervals_per_year]

    # Append the data to the list of datasets
    truck_schedule.append(truck)

truck_schedule = np.array([truck_schedule])

#%% EV charging
non_EV_t = 8# import

def generate_ones_EV():
    return [1] * random.randint(28, 36)                                    # working day
        of 7 to 9 hours

def generate_zeros1_EV():
    return [0] * random.randint(26, 36)                                    # working day
        starts between 06:30-09:00

def generate_zeros2_EV():
    return [0] * 60

EV_schedule = []

for charger in range(105):
    EV = []
    for day in range(365):
        day = []
        zeros_block = generate_zeros1_EV()
        day.extend(zeros_block)
        ones_block = generate_ones_EV()
        day.extend(ones_block)
        zeros_block = generate_zeros2_EV()
        day.extend(zeros_block)

        day = day[:96]
        EV.extend(day)
    EV = EV[:num_intervals_per_year]
    EV_schedule.append(EV)

EV_schedule = np.array([EV_schedule])

#%% E-boiler

def generate_ones_Eboiler_winter():
    return [1] * random.randint(16, 91)

def generate_zeros_Eboiler_winter():
    return [0] * random.randint(16, 19)

def generate_ones_Eboiler_summer():
    return [1] * random.randint(16, 19)

def generate_zeros_Eboiler_summer():
    return [0] * random.randint(16, 91)

def generate_ones_Eboiler():
    return [1] * random.randint(16, 31)

def generate_zeros_Eboiler():
    return [0] * random.randint(16, 31)

# Initialize the list to store all datasets
Eboiler_data1 = []
Eboiler_data2 = []

```

```python
# Generate the data for each heated tank
for i in range(num_modes_Eboiler):
    data1 = []
    while len(data1) < 5840:
        ones_block = generate_ones_Eboiler_winter()
        data1.extend(ones_block)
        zeros_block = generate_zeros_Eboiler_winter()
        data1.extend(zeros_block)
        data1 = data1[:5840]
    while 5840 <= len(data1) < 14600:
        ones_block = generate_ones_Eboiler()
        data1.extend(ones_block)
        zeros_block = generate_zeros_Eboiler()
        data1.extend(zeros_block)
        data1 = data1[:14600]
    while 14600 <= len(data1) < 26280:
        ones_block = generate_ones_Eboiler_summer()
        data1.extend(ones_block)
        zeros_block = generate_zeros_Eboiler_summer()
        data1.extend(zeros_block)
        data1 = data1[:26280]
    while 26280 <= len(data1) < 29200:
        ones_block = generate_ones_Eboiler()
        data1.extend(ones_block)
        zeros_block = generate_zeros_Eboiler()
        data1.extend(zeros_block)
        data1 = data1[:29200]
    while 29200 <= len(data1) < 35040:
        ones_block = generate_ones_Eboiler_winter()
        data1.extend(ones_block)
        zeros_block = generate_zeros_Eboiler_winter()
        data1.extend(zeros_block)

    data1 = data1[:num_intervals_per_year]
    Eboiler_data1.append(data1)

# Generate the data for each heated tank
for i in range(num_modes_Eboiler):
    data = []
    while len(data) < 5840:
        zeros_block = generate_zeros_Eboiler_winter()
        data.extend(zeros_block)
        ones_block = generate_ones_Eboiler_winter()
        data.extend(ones_block)
        data = data[:5840]
    while 5840 <= len(data) < 14600:
        zeros_block = generate_zeros_Eboiler()
        data.extend(zeros_block)
        ones_block = generate_ones_Eboiler()
        data.extend(ones_block)
        data = data[:14600]
    while 14600 <= len(data) < 26280:
        zeros_block = generate_zeros_Eboiler_summer()
        data.extend(zeros_block)
        ones_block = generate_ones_Eboiler_summer()
        data.extend(ones_block)
        data = data[:26280]
    while 26280 <= len(data) < 29200:
        zeros_block = generate_zeros_Eboiler()
        data.extend(zeros_block)
        ones_block = generate_ones_Eboiler()
        data.extend(ones_block)
        data = data[:29200]
    while 29200 <= len(data) < 35040:
        zeros_block = generate_zeros_Eboiler_winter()
        data.extend(zeros_block)
        ones_block = generate_ones_Eboiler_winter()
        data.extend(ones_block)
    data = data[:num_intervals_per_year]
    Eboiler_data2.append(data)

```

```python
Eboiler_data_full = np.array(Eboiler_data1) + np.array(Eboiler_data2)

#%% Other
other_cols = 20                                                         # amount of 'other' assets operating at random times

#%% EMA model
def energy_problem(n_terminals=None, n1_barge=None, n2_barge=None, n3_barge=None, n4_barge=None, shore_barge=None, n1_SGV=None, n2_SGV=None,
                   n3_SGV=None, n4_SGV=None, shore_SGV=None, n1_mixers=None, n2_mixers=None, n3_mixers=None, n4_mixers=None, n1_comp=None,
                   n2_comp=None, n3_comp=None, n4_comp=None, P_DVI=None, n1_DVI=None, n2_DVI=None, n3_DVI=None, n4_DVI=None, n1_truck=None,
                   n2_truck=None, n3_truck=None, n4_truck=None, n1_EV=None,n2_EV=None, n3_EV=None, n4_EV=None, P_other=None, P_Eboiler=None,
                   P_elec23=None, P_elec4=None,
                   P_gen=None, P_bat=None, P_CHP=None, A1_solarPV=None, A2_solarPV=None, A3_solarPV=None, A4_solarPV=None,
                   n_wind=None):
    if shore_barge == 0:
        Barge1 = np.array(full_barge_schedule[:n1_barge])
        Barge2 = np.array(full_barge_schedule[8:n2_barge+8])
        Barge3 = np.array(full_barge_schedule[33:n3_barge+33])
        Barge4 = np.array(full_barge_schedule[48:n4_barge+48])
        P_barge1 = 50 * sum(Barge1)
        P_barge2 = 50 * sum(Barge2)
        P_barge3 = 50 * sum(Barge3)
        P_barge4 = 50 * sum(Barge4)
    elif shore_barge == 2:
        Barge1 = np.array(full_barge_shore_schedule[:n1_barge])
        Barge2 = np.array(full_barge_shore_schedule[8:n2_barge+8])
        Barge3 = np.array(full_barge_shore_schedule[33:n3_barge+33])
        Barge4 = np.array(full_barge_shore_schedule[48:n4_barge+48])
        P_barge1 = sum(Barge1)
        P_barge2 = sum(Barge2)
        P_barge3 = sum(Barge3)
        P_barge4 = sum(Barge4)
    elif shore_barge == 1:
        Barge1 = np.array(part_barge_shore_schedule[:n1_barge])
        Barge2 = np.array(part_barge_shore_schedule[8:n2_barge+8])
        Barge3 = np.array(part_barge_shore_schedule[33:n3_barge+33])
        Barge4 = np.array(part_barge_shore_schedule[48:n4_barge+48])
        P_barge1 = sum(Barge1)
        P_barge2 = sum(Barge2)
        P_barge3 = sum(Barge3)
        P_barge4 = sum(Barge4)
    if shore_SGV == 0:
        SGV1 = np.array(full_SGV_schedule[:n1_SGV])
        SGV2 = np.array(full_SGV_schedule[3:n2_SGV+3])
        SGV3 = np.array(full_SGV_schedule[10:n3_SGV+10])
        SGV4 = np.array(full_SGV_schedule[15:n4_SGV+15])
        P_SGV1 = 300 * sum(SGV1)
        P_SGV2 = 300 * sum(SGV2)
        P_SGV3 = 300 * sum(SGV3)
        P_SGV4 = 300 * sum(SGV4)
    elif shore_SGV == 2:
        SGV1 = np.array(full_SGV_shore_schedule[:n1_SGV])
        SGV2 = np.array(full_SGV_shore_schedule[3:n2_SGV+3])
        SGV3 = np.array(full_SGV_shore_schedule[10:n3_SGV+10])
        SGV4 = np.array(full_SGV_shore_schedule[15:n4_SGV+15])
        P_SGV1 = sum(SGV1)
        P_SGV2 = sum(SGV2)
        P_SGV3 = sum(SGV3)
        P_SGV4 = sum(SGV4)
    elif shore_SGV == 1:
        SGV1 = np.array(part_SGV_shore_schedule[:n1_SGV])
        SGV2 = np.array(part_SGV_shore_schedule[3:n2_SGV+3])
        SGV3 = np.array(part_SGV_shore_schedule[10:n3_SGV+10])
        SGV4 = np.array(part_SGV_shore_schedule[15:n4_SGV+15])
        P_SGV1 = sum(SGV1)
        P_SGV2 = sum(SGV2)
```

```
        P_SGV3 = sum(SGV3)
        P_SGV4 = sum(SGV4)
    Mixer1 = np.array([random.choices([1, 0], mixer_utilisation, k=num_intervals_per_year) for _ in range(n1_mixers)])
    Mixer2 = np.array([random.choices([1, 0], mixer_utilisation, k=num_intervals_per_year) for _ in range(n2_mixers)])
    Mixer3 = np.array([random.choices([1, 0], mixer_utilisation, k=num_intervals_per_year) for _ in range(n3_mixers)])
    Mixer4 = np.array([random.choices([1, 0], mixer_utilisation, k=num_intervals_per_year) for _ in range(n4_mixers)])
    P_mixer1 = P_mixer * np.sum(Mixer1, axis=0)
    P_mixer2 = P_mixer * np.sum(Mixer2, axis=0)
    P_mixer3 = P_mixer * np.sum(Mixer3, axis=0)
    P_mixer4 = P_mixer * np.sum(Mixer4, axis=0)
    Comp1 = comp_data[:n1_comp]
    Comp2 = comp_data[8:n2_comp+8]
    Comp3 = comp_data[48:n3_comp+48]
    Comp4 = comp_data[68:n4_comp+68]
    P_comp1 = P_comp * sum(Comp1)
    P_comp2 = P_comp * sum(Comp2)
    P_comp3 = P_comp * sum(Comp3)
    P_comp4 = P_comp * sum(Comp4)
    DVI1 = full_DVI_schedules[:n1_DVI]
    DVI2 = full_DVI_schedules[2:n2_DVI+2]
    DVI3 = full_DVI_schedules[10:n3_DVI+10]
    DVI4 = full_DVI_schedules[14:n4_DVI+14]
    P_DVI1 = P_DVI * sum(DVI1)
    P_DVI2 = P_DVI * sum(DVI2)
    P_DVI3 = P_DVI * sum(DVI3)
    P_DVI4 = P_DVI * sum(DVI4)
    nitrob_barge1 = select_berths_barge(full_barge_schedule[:n1_barge])
    nitrob_barge2 = select_berths_barge(full_barge_schedule[5:n2_barge+5])
    nitrob_barge3 = select_berths_barge(full_barge_schedule[25:n3_barge+25])
    nitrob_barge4 = select_berths_barge(full_barge_schedule[40:n4_barge+40])
    P_nitrob_barge1 = P_nitrob_barge * np.sum(nitrob_barge1, axis=0)
    P_nitrob_barge2 = P_nitrob_barge * np.sum(nitrob_barge2, axis=0)
    P_nitrob_barge3 = P_nitrob_barge * np.sum(nitrob_barge3, axis=0)
    P_nitrob_barge4 = P_nitrob_barge * np.sum(nitrob_barge4, axis=0)
    nitrob_SGV1 = select_berths_SGV(full_SGV_schedule[:n1_SGV])
    nitrob_SGV2 = select_berths_SGV(full_SGV_schedule[3:n2_SGV]+3)
    nitrob_SGV3 = select_berths_SGV(full_SGV_schedule[9:n3_SGV]+9)
    nitrob_SGV4 = select_berths_SGV(full_SGV_schedule[15:n4_SGV]+15)
    P_nitrob_SGV1 = P_nitrob_SGV * np.sum(nitrob_SGV1, axis=0)
    P_nitrob_SGV2 = P_nitrob_SGV * np.sum(nitrob_SGV2, axis=0)
    P_nitrob_SGV3 = P_nitrob_SGV * np.sum(nitrob_SGV3, axis=0)
    P_nitrob_SGV4 = P_nitrob_SGV * np.sum(nitrob_SGV4, axis=0)
    truck1 = truck_schedule[:n1_truck]
    truck2 = truck_schedule[3:n2_truck+3]
    truck3 = truck_schedule[13:n3_truck+13]
    truck4 = truck_schedule[21:n4_truck+21]
    P_truck1 = P_truck * np.sum(truck1, axis=(0,1))
    P_truck2 = P_truck * np.sum(truck2, axis=(0,1))
    P_truck3 = P_truck * np.sum(truck3, axis=(0,1))
    P_truck4 = P_truck * np.sum(truck4, axis=(0,1))
    n_1p = n1_EV // 2
    n_1r = n1_EV - n_1p
    n_2p = n2_EV // 2
    n_2r = n2_EV - n_2p
    n_3p = n3_EV // 2
    n_3r = n3_EV - n_3p
    n_4p = n4_EV // 2
    n_4r = n4_EV - n_4p
    EV1 = EV_schedule[:n_1r]
    EV2 = EV_schedule[10:n_2r+10]
    EV3 = EV_schedule[60:n_3r+60]
    EV4 = EV_schedule[85:n_4r+85]
    P_EV1 = P_EV * np.sum(EV1, axis=(0,1))
    P_EV2 = P_EV * np.sum(EV2, axis=(0,1))
    P_EV3 = P_EV * np.sum(EV3, axis=(0,1))
    P_EV4 = P_EV * np.sum(EV4, axis=(0,1))
    P_EVs1 = P_EV1 + (P_EV * n_1p)
```

```
    P_EVs2 = P_EV2 + (P_EV * n_2p)
    P_EVs3 = P_EV3 + (P_EV * n_3p)
    P_EVs4 = P_EV4 + (P_EV * n_4p)
    P_Eboilers = P_Eboiler * sum(Eboiler_data_full)
    Other1 = np.array([[random.random() for _ in range(other_cols)] for _ in range(num_intervals_per_year)])
    Other2 = np.array([[random.random() for _ in range(other_cols)] for _ in range(num_intervals_per_year)])
    Other3 = np.array([[random.random() for _ in range(other_cols)] for _ in range(num_intervals_per_year)])
    Other4 = np.array([[random.random() for _ in range(other_cols)] for _ in range(num_intervals_per_year)])
    P_other1 = P_other * sum(Other1.T)
    P_other2 = P_other * sum(Other2.T)
    P_other3 = P_other * sum(Other3.T)
    P_other4 = P_other * sum(Other4.T)
    P_solarPV1 = np.array(P_solarPV.T * A1_solarPV)
    P_solarPV2 = np.array(P_solarPV.T * A2_solarPV)
    P_solarPV3 = np.array(P_solarPV.T * A3_solarPV)
    P_solarPV4 = np.array(P_solarPV.T * A4_solarPV)
    P_winds = np.array(P_wind * n_wind)
    if n_terminals == 4:
        P_barges = P_barge1 + P_barge2 + P_barge3 + P_barge4
        P_SGVs   = P_SGV1   + P_SGV2   + P_SGV3   + P_SGV4
        P_mixers = P_mixer1 + P_mixer2 + P_mixer3 + P_mixer4
        P_comps  = P_comp1  + P_comp2  + P_comp3  + P_comp4
        P_DVIs   = P_DVI1   + P_DVI2   + P_DVI3   + P_DVI4
        P_nitrob_barges = P_nitrob_barge1 + P_nitrob_barge2 + P_nitrob_barge3 + P_nitrob_barge4
        P_nitrob_SGVs   = P_nitrob_SGV1   + P_nitrob_SGV2   + P_nitrob_SGV3   + P_nitrob_SGV4
        P_trucks = P_truck1 + P_truck2 + P_truck3 + P_truck4
        P_EVs    = P_EVs1   + P_EVs2   + P_EVs3   + P_EVs4
        P_others = P_other1 + P_other2 + P_other3 + P_other4
        P_solarPVs = P_solarPV1 + P_solarPV2 + P_solarPV3 + P_solarPV4
        P_elec = P_elec4
    if n_terminals == 2:
        P_barges = P_barge1 + P_barge2
        P_SGVs   = P_SGV1   + P_SGV2
        P_mixers = P_mixer1 + P_mixer2
        P_comps  = P_comp1  + P_comp2
        P_DVIs   = P_DVI1   + P_DVI2
        P_nitrob_barges = P_nitrob_barge1 + P_nitrob_barge2
        P_nitrob_SGVs   = P_nitrob_SGV1   + P_nitrob_SGV2
        P_trucks = P_truck1 + P_truck2
        P_EVs    = P_EVs1   + P_EVs2
        P_others = P_other1 + P_other2
        P_solarPVs = P_solarPV1 + P_solarPV2
        P_elec = P_elec23
    else:
        P_barges = P_barge1 + P_barge2 + P_barge3
        P_SGVs   = P_SGV1   + P_SGV2   + P_SGV3
        P_mixers = P_mixer1 + P_mixer2 + P_mixer3
        P_comps  = P_comp1  + P_comp2  + P_comp3
        P_DVIs   = P_DVI1   + P_DVI2   + P_DVI3
        P_nitrob_barges = P_nitrob_barge1 + P_nitrob_barge2 + P_nitrob_barge3
        P_nitrob_SGVs   = P_nitrob_SGV1   + P_nitrob_SGV2   + P_nitrob_SGV3
        P_trucks = P_truck1 + P_truck2 + P_truck3
        P_EVs    = P_EVs1   + P_EVs2   + P_EVs3
        P_others = P_other1 + P_other2 + P_other3
        P_solarPVs = P_solarPV1 + P_solarPV2 + P_solarPV3
        P_elec = P_elec23
    P_total = P_barges + P_SGVs + P_mixers + P_comps + P_DVIs + P_nitrob_barges + P_nitrob_SGVs + P_trucks + P_EVs + P_Eboilers + P_others - P_solarPVs - P_winds
    P_total = P_total[0,5:num_intervals_per_year]                              # Due to digital square wave signal of certain components
    P_input = P_elec + P_gen + P_bat + P_CHP
    P_max_load = np.max(P_total)
    P_th_load = np.max(P_barges) + np.max(P_SGVs) + np.max(P_mixers) + np.max(P_comps) + np.max(P_DVIs) + np.max(P_nitrob_barges) + np.max(P_nitrob_SGVs) + np.max(P_trucks) + np.max(P_EVs) + np.max(P_Eboilers) + np.max(P_others)
    balance = P_max_load - P_input
```

```
    if balance > 0:
        overload = balance
    else:
        overload = 0
    return {"P_max_load": P_max_load, "overload": overload, "P_th_load": P_th_load}

energy_model = Model('EnergyModel', function=energy_problem)
energy_model.time_horizon = 1

#%% X, L
energy_model.uncertainties = [
    CategoricalParameter("n_terminals", np.array([2, 3, 4])),

    CategoricalParameter("P_elec", np.array([15000, 20000, 25000, 40000]))
]

energy_model.constants = [
    # Constant("P_elec", 20000),
    # Constant("n1_truck", 0),
    # Constant("n2_truck", 0),
    # Constant("n3_truck", 0),
    # Constant("n4_truck", 0),

    # Constant("n1_EV", 10),
    # Constant("n2_EV", 40),
    # Constant("n3_EV", 25),
    # Constant("n4_EV", 50),

    # Constant("shore_barge", 2),
    # Constant("shore_SGV", 2),

    # Constant("P_Eboiler", 0)

    # Constant("P_gen", 0),
    # Constant("P_bat", 0),

    # Constant("P_CHP", 0),

    # Constant("A1_solarPV", 0),
    # Constant("A2_solarPV", 0),
    # Constant("A3_solarPV", 0),
    # Constant("A4_solarPV", 0),

    # Constant("n_wind", 0)
    ]
energy_model.levers = [
    IntegerParameter("n1_barge", 1,  8),
    IntegerParameter("n2_barge", 7, 25),
    IntegerParameter("n3_barge", 5, 15),
    IntegerParameter("n4_barge", 7, 30),

    IntegerParameter("n1_SGV", 0, 3),
    IntegerParameter("n2_SGV", 2, 7),
    IntegerParameter("n3_SGV", 1, 5),
    IntegerParameter("n4_SGV", 2, 8),

    IntegerParameter("n1_mixers", 20,  100),
    IntegerParameter("n2_mixers", 100, 400),
    IntegerParameter("n3_mixers", 50,  200),
    IntegerParameter("n4_mixers", 150, 500),

    IntegerParameter("n1_comp", 2,  8 ),
    IntegerParameter("n2_comp", 10, 40),
    IntegerParameter("n3_comp", 5,  20),
    IntegerParameter("n4_comp", 15, 50),

    RealParameter("P_DVI", 200, 600),

    IntegerParameter("n1_DVI", 0, 2 ),
    IntegerParameter("n2_DVI", 0, 8 ),
    IntegerParameter("n3_DVI", 0, 4 ),
```

```python
    IntegerParameter("n4_DVI", 0, 10),

    CategoricalParameter("n1_truck", np.array([0, 1, 3])),
    CategoricalParameter("n2_truck", np.array([0, 2, 10])),
    CategoricalParameter("n3_truck", np.array([0, 2, 8])),
    CategoricalParameter("n4_truck", np.array([0, 2, 10])),

    CategoricalParameter("n1_EV", np.array([0, 2 , 10])),
    CategoricalParameter("n2_EV", np.array([0, 10, 40])),
    CategoricalParameter("n3_EV", np.array([0, 5 , 25])),
    CategoricalParameter("n4_EV", np.array([0, 10, 50])),

    CategoricalParameter("shore_barge", np.array([0, 1, 2])),                # 0 = None, 1 = 20%, 2 = 100%

    CategoricalParameter("shore_SGV", np.array([0, 1, 2])),                  # 0 = None, 1 = 20%, 2 = 100%

    CategoricalParameter("P_Eboiler", np.array([0, 25, 100, 250, 500])),

    IntegerParameter("P_other", 5, 50),

    CategoricalParameter("P_gen", np.array([0, 1000, 5000])),

    CategoricalParameter("P_bat", np.array([0, 1000, 5000])),

    CategoricalParameter("P_CHP", np.array([0, 12000])),

    CategoricalParameter("A1_solarPV", np.array([0, 500, 10000])),
    CategoricalParameter("A2_solarPV", np.array([0, 1500, 80000])),
    CategoricalParameter("A3_solarPV", np.array([0, 1000, 50000])),
    CategoricalParameter("A4_solarPV", np.array([0, 1500, 100000])),

    CategoricalParameter("n_wind", np.array([0, 1, 2]))
]
energy_model.outcomes = [
    ScalarOutcome("P_max_load"),
    ScalarOutcome("overload"),
    ScalarOutcome("P_th_load")
]

#%% Perform experiments
# 2 uncertainties, 41 levers
results = perform_experiments(energy_model, scenarios=20, policies=400)
#%%
experiments, outcomes = results

#%% outcomes - run
# coverage: fraction of data in 'outputs of interest'
# density: fraction of cases in 'outputs of interest'
x = experiments
y2 = outcomes["overload"] > 15000

#%% PRIM search - run
prim_alg = prim.Prim(x, y2, threshold=0.8)

box1 = prim_alg.find_box()
print("PRIM box 1:\n")
box1.show_tradeoff()
box1.inspect()
box1.inspect(style='graph')
box1.show_pairs_scatter()
plt.show()

#%% Another PRIM box 2
print("PRIM box 2:\n")
box2 = prim_alg.find_box()
box2.show_tradeoff()
box2.inspect()
box2.inspect(style='graph')
box2.show_pairs_scatter()
```

```
#%% And another PRIM box 3
print("PRIM␣box␣3:\n")
box3 = prim_alg.find_box()
box3.inspect()
box3.show_tradeoff()
box3.inspect(style='graph')
box3.show_pairs_scatter()
plt.show()

#%% Feature scoring
Y1 = outcomes["P_max_load"]
Y2 = outcomes["overload"]
y = {"P_max_load":Y1, "overload":Y2}
y_1 = {"P_max_load":Y1}
y_2 = {"overload":Y2}
fs = feature_scoring.get_feature_scores_all(x, y)
sns.heatmap(fs, cmap="viridis", annot=True)

plt.show()

fs = fs.nlargest(len(fs), 'overload')
fs_display = pd.concat([fs.head(20), fs.tail(20)])
```