

Gridmaster HIC Rotterdam



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Contents

Glossary	4
Units and abbreviations	9
Summary	10
1. Introduction	13
2. Theoretical foundations	23
3. Gridmaster method	25
4. Case study description	33
5. Development of scenario space and coherent energy system model	34
6. Creation of storyline-overload relations	72
7. Development of strategic direction for a robust, adaptive investment path	87
8. Discussion	118
9. Conclusions	128
10. Recommendations	131
11. References	138
Appendix A: evolution of the project focus	141
Appendix B: scenario space details	143
Appendix C: motivation for choices on subsystem division of the HIC Rotterdam energy system	144
Appendix D: current situation of the HIC Rotterdam energy system	147
Appendix E: super structure of (potential) energy system of the HIC Rotterdam	148
Appendix F: Results of PRIM-analyses for identification of drivers for specific overload patterns for 380 kV-, H₂-, ODO- and NODO-networks	150

Glossary

Adaptive investment	An investment that can be initiated in the future depending on the probability that the certain trigger conditions of the energy system, the adaptive investment is linked at, are met in the future. Those trigger conditions will lead to an increased transport capacity demand for which an adaptive investment is necessary to prevent capacity bottlenecks.
Autothermal Reforming plant	Plant that produces H ₂ from a fossil energy feedstock (fossil methane, refinery gas, petcoke). This technology will be implemented in the HIC Rotterdam in case H-vision will be implemented.
Blue H ₂	H ₂ produced based on the conversion of a fossil energy source (fossil methane, refinery gas, petcoke). The produced CO ₂ is captured and permanently stored.
Carbon Capture and Storage	A technology that captures CO ₂ from concentrated sources for subsequent storage in permanent storage locations.
Conversion asset	An asset that transforms an energy and/or material input flow towards another energy and/or material output flow. Examples of conversion assets are factories or energy generation units, like methane fired power plants.
Carbon monoxide plant	Carbon monoxide production plant. The carbon monoxide plant in the HIC Rotterdam is part of the chlorine cluster.
Direct Air Capture plant	Conversion asset technology that captures CO ₂ from air. This conversion technology could possibly be integrated into the energy system of the HIC, providing CO ₂ as a feedstock for hydrocarbon material / fuel production.
Driving external factor	Identified external factor that significantly contributes to the evolution of transport capacity demand over time
Electricity network	The 380 kV-, 150 kV- and Medium Voltage-network that was in scope of the case study Gridmaster HIC Rotterdam.
Energy infrastructure	The integrated energy infrastructure, comprising the electricity-, H ₂ - and methane networks.
Energy system evolution pathway	A potential evolution of the energy system, excluding the energy infrastructure component, in a specific geographical area in the period from now to the end of the planning horizon (e.g. in 2050).
External factor	A dimension of the scenario space. An external factor has several values. Each value affects the scenario generation in a specific way.
Fischer-Tropsch plant	A Fischer-Tropsch plant converts a mixture of carbon monoxide and H ₂ into hydrocarbons. A Fischer-Tropsch plant can be integrated into the energy system of the HIC Rotterdam. Potential incorporation of Fischer-Tropsch plants into the HIC Rotterdam was part of the developed scenario space for the case study Gridmaster HIC Rotterdam.
Fossil methane	Methane of fossil origin.
G-gas	A specific methane gas quality.
Gas	Collective name for fossil methane, green methane and H ₂ .
Green H ₂	H ₂ stemming from an H ₂ O electrolysis plant.

Green methane	Methane stemming from processes that convert biomass or CO ₂ from capture from air into methane.
Gridmaster method	The developed long-term investment planning method for integrated energy infrastructure within the context of deep uncertainty of the evolution of the energy system.
H-vision	A possible investment program in the HIC Rotterdam that aims to install blue H ₂ production capacity (via an ATR) and replace part of the refinery gas that is used as feedstock for furnaces / boilers with blue H ₂ .
H ₂ -network	The to be developed H ₂ -network for the HIC Rotterdam to be operated by Gasunie. This network is part of the considered integrated energy infrastructure in the executed case study.
H ₂ O electrolysis plant	A group of technologies that convert water and electricity into H ₂ , oxygen and residual heat. The produced H ₂ is referred to as 'green H ₂ '.
HIC Rotterdam	Harbor Industrial Cluster of Rotterdam.
HTLH-network	Part of the considered methane infrastructure in the Gridmaster case study HIC Rotterdam.
Infrastructure element	Building block for an energy network. The network is constructed of nodes and links. An infrastructure element is either a specific node or link.
Integrated energy infrastructure	The energy infrastructure that has been considered in the case study HIC Rotterdam. This comprised the methane networks (HTLH-, ODO-, NODO-networks), H ₂ -network and electricity networks (380 kV-, 150 kV-, Medium Voltage-networks) for the HIC Rotterdam.
Investment path	A series of realized investments over the planning period for the considered energy infrastructure. Investment rules that trigger investments based on conditions of the energy system can be part of an investment path.
Investment plan	A series of planned investments over the planning period for the considered energy infrastructure. Investment rules that trigger investments based on conditions of the energy system can be part of an investment path.
Lever	A dimension of a policy factor that is controlled by the (group of) decision-maker(s). The investment path for 380 kV-investments, used in the case study Gridmaster HIC Rotterdam, is an example of a lever.
Long-term robustness performance on capacity	A performance attribute of an investment path that expresses the ability of the investment path to successfully facilitate scenarios in the long run.
Methane network	The methane network that was in scope of the case study Gridmaster HIC Rotterdam. This methane network was divided in the HTLH-, ODO-, and NODO- subnetworks.
Metric	An indicator that measures a certain characteristic of an investment path.
MIEK investment path	The investment path for electricity, methane and H ₂ -infrastructure for the HIC Rotterdam that is part of the Dutch Multi-year program Infrastructure, Energy and Climate in the Netherlands (<i>Meerjarenprogramma Infrastructuur, Energie en Klimaat</i>).
Model cluster	Part of the multi-model simulation tool.

MV-network	Medium Voltage network (25, 50, 66 kV).
NODO-network	Part of the considered methane infrastructure in the Gridmaster case study HIC Rotterdam.
ODO-network	Part of the considered methane infrastructure in the Gridmaster case study HIC Rotterdam.
Overload capacity	Variable that is used for the expression of the overload magnitude of a gas infrastructure element or network in a certain reference year in the case study Gridmaster HIC Rotterdam.
Overload class	A range of overload magnitudes for an energy network that is used to 1) express the impact of energy infrastructure in long-term energy system evolution pathways and 2) to distinguish scenarios that can be facilitated by an investment path from scenarios that cannot be facilitated by an investment path.
Overload duration	Variable that is used for the expression of the overload magnitude of an electricity infrastructure element or network in a certain reference year in the case study Gridmaster HIC Rotterdam.
Peak shaver	An asset that is connected to the methane network in HIC Rotterdam that provides enhanced methane supply to the built environment in cold weather conditions.
Petcoke	A byproduct of an oil refinery that is used as fuel for on site utilities production.
Planning horizon	The time-period that is considered for the investment planning of energy infrastructure. In the case study, the planning horizon covers 2022 – 2050.
Polyurethane cluster	A group of production plants that are part of the chlorine cluster of the HIC Rotterdam. These plant produce polyurethane and related products.
Polyvinyl chloride plant	Production plant of polyvinyl chloride. The polyvinyl chloride plant is part of the chlorine cluster in the HIC Rotterdam.
PRIM	Patient Rule Induction Method. This is a factor mapping approach aiming to identify sensitive ranges of uncertain factors that are likely to cause a particular outcome. PRIM-analysis is used in the Gridmaster method to obtain storyline-overload relations and insights into the storyline drivers for overload magnitude developments in energy infrastructure.
PRIM-box	A result of a PRIM-analysis. A PRIM-box is a very concise representation, for typically only a limited set of dimensions of the model input space is restricted
Project	The Gridmaster HIC Rotterdam project: the project that is described in this report.
Refinery gas	A byproduct of an oil refinery that is used as fuel for on site utilities or H ₂ -production.
Reverse Water Gas Shift plant	A plant in which carbon monoxide is produced from CO ₂ and H ₂ . This plant can be part of a technology configuration that potentially can be integrated in the HIC Rotterdam. This plant was part of a technology lego brick that was used in the scenario space design in the case study Gridmaster HIC Rotterdam.

Robustness performance on investment costs	A performance attribute of an investment path that expresses the magnitude of investment costs across many scenarios.
Scenario	A description of a potential transient pathway of the energy system evolution in a certain geographic area over the planning horizon. A scenario is leading to a certain evolution of transport capacity demand. A scenario is part of the scenario space.
Scenario space	A scenario space is constructed from external factors and is aimed at encompassing all plausible scenarios relevant for energy infrastructure planning in a certain geographic area.
Short-term robustness performance on capacity	A performance attribute of an investment path that expresses the ability of the investment path to successfully facilitate scenarios in the short run.
Simulation run	A single computational experiment in which the evolution of overloads of energy infrastructure elements is examined for a combination of an investment path and a scenario.
Site	A part of the HIC Rotterdam with a specific geographic location that is part of a specific energy subsystem. At a site conversion assets can be located and a site is connected to energy infrastructure for the exchange of energy carriers from and to this site.
Steam cycle	A process in which steam is generated in a boiler, that is subsequently expanded steam through a turbine to extract work, and thus generating electricity. A steam cycle can be part of technology lego bricks that have been applied to construct the scenario space in the case study HIC Rotterdam.
Steam Methane Reforming plant	Methane based H ₂ -production plant. Refinery gas can also be a feedstock for this plant.
Storage asset	An asset where an energy carrier can be stored for a certain period, like a battery, gas, liquid or solid storage.
Storyline	A storyline is a set of scenarios that represents a certain subspace of the scenario space that is relevant for energy infrastructure planning.
Storyline driver	A storyline driver corresponds to adaptation tipping point conditions that, when occurring without adaptive investment, will lead to a certain overload magnitude on the long run. An adaptive investment should be coupled to a storyline driver to prevent future overload conditions in case the energy system evolution leads into the direction of the storyline driver.
Storyline factor	A storyline factor is a dimension of the storyline space that is relevant for the evolution of energy infrastructure planning requirements.
Storyline-overload relation	The relation between a storyline and the corresponding range of overload evolution over the planning horizon.
Storyline space	Space built from independent storyline factors.
Stress testing	The core principle of the Gridmaster method in which the overload development over time in energy infrastructure is examined for an investment path in many scenarios.
Structural change	Structural change relates to a change of the installed base of conversion assets in the considered geographical area or to changing trends in energy exchange between the geographical area and its surroundings.

Syncrude	Product output of a technology lego brick that represents a technology configuration for synthetic fuel production.
Synthetic fuel production	The production of hydrocarbon fuels from CO ₂ and H ₂ . Synthetic fuel production growth in various technology configurations was part of the developed scenario space for the case study Gridmaster HIC Rotterdam.
Technology lego brick	A technology lego brick represents a certain energy conversion technology with a specific capacity and spatial footprint. In a scenario these lego bricks can be installed at a site, forming a part of the energy system on this site. In the case study, technology lego bricks were used in the modeling of energy system configurations of the HIC.
Technology lego building	The collection of lego bricks at a site during a reference year of a scenario is called a technology lego building. A lego building at a site can be seen as the energy system at a site level.
Titanium dioxide plant	Plant that produces titanium dioxide and is part of the chlorine cluster in the HIC Rotterdam.
Topology factor	A factor that was used for the calculation of the overload value for a 380 kV- or 150 kV-network, based on the overload values for the infrastructure elements the network is composed of.
Utilities	In the case study Gridmaster HIC Rotterdam utilities is referred to as the group comprising the energy carriers steam, High Temperature heat and electricity.
Vinylchloride monomer plant	Production plant of vinylchloride monomer that is a feedstock for PVC production. The vinylchloride monomer plant is part of the chlorine cluster in the HIC Rotterdam.

Units and abbreviations

ATR	Autothermal Reforming plant
CCS	Carbon Capture and Storage
CO plant	Carbon monoxide plant
CO ₂	Carbon dioxide
DAC	Direct Air Capture plant
FT	Fischer-Tropsch plant
GW_H ₂	Gigawatt H ₂
GW*km	Gigawatt*kilometer
GWe	Gigawatt electricity
H ₂	Hydrogen
MW_H ₂	Megawatt H ₂
MWe	Megawatt electricity
MWh	Megawatt hour
PUR-cluster	Polyurethane cluster
PVC plant	Polyvinyl chloride plant
RWGS plant	Reverse Water Gas Shift plant
SMR	Steam Methane Reforming plant
TiO ₂ plant	Titanium dioxide plant
TWh/y	Terrawatthour / year
VCM plant	Vinylchloride monomer plant

Summary

Decision-making on integrated energy infrastructure is challenging by deep uncertainty

The evolution of the energy system over the coming years is deeply uncertain. At the same time, investments in energy infrastructure are costly, which present major challenges for long-term energy infrastructure investment planning. How can the impact of energy infrastructure be better incorporated in decision-making on long-term socially desired energy system evolution pathways? Which investments in energy infrastructure should be planned given the deep uncertainty of the long-term evolution of the energy system? How can the risks of stranded assets be balanced with the added value of enabling potential future energy system evolutions?

Developed Gridmaster method to support decision-making under deep uncertainty

In the Gridmaster HIC Rotterdam project these questions have been addressed. As part of this project, a decision-support method (hereafter: Gridmaster method) has been developed for long-term planning of integrated energy infrastructure, in the context of the deep uncertainty about the energy system evolution. The energy infrastructure investment planning challenge in the Harbor Industrial Cluster in Rotterdam (HIC Rotterdam), the largest petrochemical cluster of Europe, served as a case study for developing and partially testing of the Gridmaster method, as well as the associated digital tools.

The developed Gridmaster method provides decision support information for two major decision-making processes: 1) the decision-making process on socially desirable long-term energy system pathways that should be supported by integrated energy infrastructure; 2) the decision-making process on the strategic direction for no regret and adaptive investments in integrated energy infrastructure for the facilitation of these socially desirable energy system pathways.

Application of the Gridmaster method leads to insights into no regret investments on the medium term enabling the facilitation of a wide range of possible energy system evolution scenarios in this timeframe. Furthermore, it identifies drivers for transport capacity evolution on the long term, leading to insights into adaptive investments. These investments will be planned, only in case certain drivers leading to increased transport capacity demand seem plausible. In case these drivers do not seem plausible, these investments will not be planned. This adaptiveness of the investment plan, limits the risk on stranded assets while it increases the capability to facilitate future long term energy system scenarios.

The foundation for the Gridmaster method is the Robust Decision Making approach as established in academia [1, 2]. This approach has been applied to the coordinated investment planning challenge of energy infrastructure. The core principle of the Gridmaster method is stress testing of an investment path across many potential scenarios, where a scenario describes a potential realization of how the energy system could evolve over time with respect to a wide variety of underlying uncertainties such as the emerging of new factories, new power plants, and / or changing energy exchange of the considered geographic area with the environment. The stress testing yields insights into the range of potential overload development over time in the considered energy networks. A large scenario space of long-term energy system evolution pathways, combined with a coherent multi-model of the energy system enables this process. Subsequent data analyses reveal insights into robust and adaptive investments.

Added value for grid operators in decision-making on robust and adaptive investments

In the Gridmaster HIC Rotterdam case study, approximately 10,000 potential scenarios have been considered as the representation of the deep uncertainty about the energy system evolution. Using this amount of scenarios leads to a better representation of the real deep uncertainty, relevant for decision-making on energy infrastructure investments, compared to the few scenario (cornerstone) points that are typically considered in the current practice of grid planning.

In total 11 storyline drivers for the 380 kV- and H₂-networks have been identified by data analyses. A storyline driver is a specific set of scenario developments over time that drives a particular overload magnitude evolution for energy infrastructure in the long run. These storyline drivers are the adaptation tipping point conditions for which specific adaptive investment packages should be designed. In case the energy system evolution progresses into the direction of adaptation tipping point conditions, the linked adaptive investment package should be planned, enabling the facilitation of the evolution of the energy system. These storyline drivers are the vital developments that need to be monitored for the timely adaptation of the investment path. All other possible scenario developments are less relevant for long-term energy infrastructure planning. It should be noted that it is impossible, with the current investment planning practice, to identify these 11 storyline drivers as scenario points. Upfront determination of storyline drivers without modelling, that is part of the current practice, is not achievable given the vast amount of plausible scenarios and unknown impact of these scenarios on the overload conditions of the considered energy infrastructure. Especially, since several of these storyline drivers consist of combined developments of different external factors. The 11 storyline drivers cannot, however, be applied right away for the development of a robust, adaptive investment path for the 380 kV- and H₂-networks due to an insufficiently validated scenario space and multi-model simulation tool for these networks. The linking of adaptive investments to storyline drivers has not been conducted in the project.

For the Medium Voltage network no regret investments have been identified that can lead to a reduction of the maximum investment peak for this network. Reduction of the maximum investment peak is relevant since this can reduce the risk of non facilitation of the energy system evolution. These findings in the project have supported a real decision-making process for investments in this network.

The developed scenario space, the largest part of the multi-model simulation tool and the visualization tool is publicly available and can be used in future work. Some parts of the multi-model and data input are not publicly published due to either confidentiality reasons or due to too limited validation of the used model part.

The following key conclusions have been drawn:

- Although the developed Gridmaster method can be further improved on most aspects, the method looks promising in:
 - providing information on the impact of energy infrastructure in the decision-making process on long-term evolution pathways of a socially desirable energy system.
 - creating a strategic direction for a robust, adaptive investment path for integrated energy infrastructure.
- Participatory modeling, in which various organizations cooperate in the development and building of energy system modeling tools, appears an effective means for the development of the Gridmaster method.
- In the developed scenario space, several potential path dependencies for the energy system evolution have been successfully modeled. Path dependency is important to consider for planning of energy-infrastructure under deep uncertainty.

- The calculated robustness performances on capacity for the tested investment path for HIC Rotterdam confirms the added value of coordination of long-term investment planning for the individual energy networks.
- The developed scenario space and multi-model simulation tool require a thorough further validation and corresponding improvement to support real decision-making on long-term planning of integrated energy infrastructure for the HIC Rotterdam.
- Most requirements for a method that is able to create a strategic direction for a robust, adaptive investment path of integrated energy infrastructure are met by the developed Gridmaster method. Only some doubt exists whether the application of the Gridmaster method for a specific energy system scope can be done within an acceptable timeframe.

Development effort required for practical application as decision support means

In the decision-making on the follow-up of the Gridmaster HIC Rotterdam project, it is recommended to consider the advantages of a Gridmaster method implementation as a decision support practice and the associated costs for the realization of this implementation. Part of these costs include 'investment costs' for the creation of 'Gridmaster standards' for 1) an industrial cluster, 2) a city, 3) a rural region, 4) a province and 5) the Dutch main energy infrastructure. Furthermore, the expected exploitation costs and costs for the integration of Gridmaster processes into grid operator organizations need to be considered.

In case it is decided to continue with the development of the Gridmaster method and associated digital tooling, the key recommendations for future work are to:

- Test the Gridmaster method process steps that have not been tested in the current project.
- Intensify the interactions with decision-makers in future Gridmaster projects.
- Intensify interactions with grid strategists / strategy experts in future Gridmaster projects.
- Execute a plausibility check for the developed scenario space with the scenario space at the higher scale level in order to improve the number of plausible scenarios encompassed in the designed scenario space.
- Develop 'Gridmaster-standards' for 1) an industrial cluster, 2) a city, 3) a rural region, 4) a province and 5) the Dutch national main energy infrastructure.
- Actively involve the academic community for the acceleration of removing barriers for the implementation of the Gridmaster method.
- Thoroughly validate the developed scenario space and multi-model tool for the HIC Rotterdam case and to resolve the found weaknesses.

1. Introduction

1.1 Background

1.1.1 Problems with current investment planning method energy infrastructure

The world is heading towards a CO₂-neutral energy system in 2050. This transformation of the energy system will lead to fundamentally different requirements for energy infrastructure.

In the last decades, the basis for long-term investment planning for energy infrastructure in the Netherlands was to facilitate all future developments of the energy system. This basis is currently questioned since the vast shift of the energy system towards a CO₂ neutral energy system in less than 30 years spurs the societal debate on which energy system evolution pathways are societally desirable. Several energy system evolution pathways require massive investments in energy infrastructure leading to a huge spatial impact and high investment cost. The potential spatial impact is that huge spatial areas, currently exploited for societal functions like housing and nature, should be converted towards locations for energy infrastructure. Given the required change in spatial area function and huge investment costs for energy infrastructure in certain scenarios for long-term energy system evolution, it is societally desirable to make a societal assessment on long-term options for the energy system evolution. In which energy system evolution pathways the societal benefits of the energy system evolution are higher than the disadvantages? By answering this question, more clarity is given to the grid operators on the uncertainty they have to deal with for long-term capacity planning of energy infrastructure. Furthermore, governmental organizations can timely make arrangements with stakeholders that are affected by the change of spatial area function (from the current function towards energy infrastructure location function). Grid operators can positively contribute to support this decision-making on long-term societally desirable energy transition pathways, by providing information about the long-term impact of energy infrastructure in scenarios for the long-term evolution of the energy system.

At present, it is unclear what the main development direction of energy systems relevant for energy infrastructure investment planning will be. In other words, it is deeply uncertain how the energy transport capacity requirements for the energy infrastructure will evolve. For grid operators, this uncertainty of energy transition pathways poses a major strategic challenge: which future-proof investments should be made to facilitate different decarbonization pathways of the energy system, while minimizing the risk of stranded assets?

Given the long lead times for the realization of additional transport capacity, grid operators cannot wait until connected parties have decided to change their requirements for energy extraction from or injection to the energy infrastructure. Furthermore, if grid operators offer prospects for long-term transport capacity development, they reduce the uncertainty for organizations that consider investments in energy conversion and / or storage assets. In this way, grid operators will accelerate the energy transition by lowering the investment risks for organizations that invest in energy conversion and / or storage assets. Therefore, an investment plan for integrated energy infrastructure with a long-term view is socially desirable. Consequently, grid operators need to anticipate future transport capacity developments. However, these developments are very uncertain due to the dependency on future decisions by other stakeholders on their energy requirements, and (dis)investments in energy conversion and storage assets¹. In addition, the future investment decisions of

¹ Conversion asset: an asset that transforms an energy and/or material input flow towards another energy and/or material output flow. Examples for conversion assets are factories or energy generation units.

other grid operators in the same geographic area amplify this uncertainty due to interdependencies between different infrastructure types, and their impact on the energy system evolution. The challenge for a grid operator is how to deal with the deep uncertainties about the evolution of the energy system for its long-term investment planning. In addition, coordination of investment planning for the energy networks a grid operator owns, with investment planning for energy networks that are owned by other grid operators is another challenge for a grid operator that is aiming for effective, future proof investments.

In the current practice of investment planning for energy infrastructure, individual grid operators develop a relatively limited number of scenario (cornerstone) points² (typically 3-4) for possible (very) long-term future states of the energy system in order to define the uncertainty space for planning their infrastructure investments. The scenario (cornerstone) points are assumed to be potential energy system states at the end of the planning horizon. The actual energy system evolution is expected to progress between trajectories from the current energy system state to scenario (cornerstone) points at the end of the planning horizon. These scenario (cornerstone) points are constructed via an open process in which experts and a number of key stakeholders define qualitative storylines, that are subsequently translated to quantitative scenarios. For each scenario, the transport capacity requirements are determined, and investment needs are identified to shift the current infrastructure towards an infrastructure that is capable of facilitating the envisioned future energy system. After that, investment pathways from the current moment to the reference year of the scenario are drafted. The resulting investment pathways serve as input for the decision-making process on investments for energy infrastructure. Furthermore, this information is used as input for policy making by governmental organizations to nudge the energy system towards a CO₂-neutrality in 2050.

This current practice of individual investment planning for energy infrastructure has the following shortcomings:

1. Suboptimal engagement of stakeholders and suboptimal contribution to societal dialogue on desirable long-term energy system evolution pathways. Stakeholders including multinational companies, non-governmental and governmental organizations, who each may have their own vision of how the energy system will evolve, also have an interest in knowing whether their visions can be supported by the energy infrastructure. In case these visions differ from the used scenarios, it is impossible to know whether or not their visions can be supported. A more inclusive investment planning method that better incorporates stakeholder scenario input into the process would improve strategic decision-making processes across different stakeholders, leading to a more robust investment plan capable of supporting societally desirable energy system evolution pathways. Furthermore, a more in-depth dialogue with stakeholders will support the identification of societally desirable system integration opportunities.
2. The use of too few scenarios as basis for insights in potential transport requirement evolution pathways. The combination of independent developments that can impact the energy system evolution leads to a vast number of plausible scenarios. Although scenario (cornerstone) points, used in the current investment planning method, aim to capture the possible scenario space of energy system evolution, it is impossible

Storage asset: an asset where an energy carrier can be stored for a certain period, like a battery, gas, liquid or solid storage.

² Sometimes cornerstone scenario points are used which are targeted to be extreme energy system states at the end of the planning horizon. Otherwise, not 'extreme' scenario points are used at the end of the planning horizon. In some studies, next to the scenario points at the end of the planning horizon, also some intermediate scenario points are used.

to cover all possible future states of the energy system at the end of the planning horizon, given the limited number of scenario (cornerstone) points.

3. The focus on end state scenarios instead of transient scenarios. Although the current practice uses some scenario points in the period between now and the end of the planning horizon, it insufficiently covers the broad range of possible energy system evolution pathways over time. Furthermore, the current practice is insufficiently capable to take path dependencies in the evolution of the energy system into account. Insights into path dependencies are relevant when developing a robust, adaptive investment plan for integrated energy infrastructure. This leads to a lack of information for grid operators about when and how to adapt their investment plan as the future unfolds.
4. A static, rather than adaptive investment plan. The flexibility of adaptive plans is a key means of achieving decision robustness. While the future is unfolding, many deep uncertainties will turn into real events. Having an adaptive plan allows decisionmakers to adapt the implementation of the plan in response to these developments [3].
5. The individual investment planning approach by grid operators. Although the cooperation between Transmission System Operators and Distribution System Operators, responsible for energy infrastructure investments, has been improving in recent years in the Netherlands, current practice is that their energy infrastructure investment plans are not fully aligned. Unaligned investment planning leads to unknown impacts on the investment plans of each grid operator and the potential of the energy infrastructure to support long-term energy system evolution scenarios.

As a result of these shortcomings, the current practice of investment planning is not fully capable of handling the deep uncertainty of the energy system evolution, and may lead to the following negative outcomes:

- An increased risk of a societally undesirable development of the energy system due to the inadequate incorporation of the impact of energy infrastructure in decision-making on policies that are aimed to nudge the long-term evolution of the energy system into a societally desired direction.
- An increased risk of underinvestment on certain corridors, resulting in insufficient transport capacity and bottlenecks for various energy carriers, which could hinder a timely energy transition.
- An increased risk of unnecessary overinvestments, which ultimately become stranded assets.

1.1.2 New investment planning method need

The identified shortcomings of the current practice call for a new investment planning method that can properly deal with deep uncertainty in a multi-stakeholder decision-making context and is capable to align investment plans for multiple energy infrastructures (hereafter: integrated energy infrastructure). To this end, a consortium consisting of TenneT, Gasunie, Stedin, the Port of Rotterdam Authority, the Province of Zuid-Holland, the Municipality of Rotterdam, SmartPort, the Delft University of Technology, Siemens, TNO and Quintel started an initiative - called "Gridmaster" - to develop a methodology and associated digital tools to support decisionmakers in policymaking for steering of the long-term evolution of the energy system and for developing investment plans for integrated energy infrastructure. This new method is aimed to address the above mentioned shortcomings of the current practice.

In the development of the new investment planning method (hereafter: the Gridmaster method) the energy infrastructure planning of the HIC Rotterdam serves as a case study. In this case study the capability of the Gridmaster method to develop a future-proof investment plan for electricity, hydrogen and methane

infrastructure for this industrial cluster is partially tested. The MIEK investment path³ for the HIC Rotterdam was used in the various process steps of the developed Gridmaster method. This study builds on the “Windmaster” case study [4], in which a participatory modeling approach was used to identify investment strategies for the HIC Rotterdam.

The majority of the above text stems from [5].

1.2 Research questions and objectives

The following research questions were addressed in the Gridmaster HIC Rotterdam project (hereafter: the project):

- How can the current practice of long-term investment planning for energy infrastructure be expanded and adapted to better inform the decision-making process on societally desirable evolutions of the energy system with information about the impact of energy infrastructure?
- How can the current practice of long-term investment planning for energy infrastructure be expanded and adapted to develop robust, adaptive investment plans for integrated energy infrastructure within the context of deep uncertainty of the energy transition?
- What is the robustness of the developed MIEK investment path for HIC Rotterdam and what decision relevant information can support the decision-making on the long-term system objective the grid operators should aim for to facilitate with integrated energy infrastructure?

From these research questions the following project objectives have been derived:

1. The development of a new method for long-term adaptive grid planning that enables the creation of robust, adaptive integrated investment plans for energy infrastructure within the context of deep uncertainty of the energy transition.
2. The development of a relevant scenario space for the development of a strategic direction for a robust, adaptive investment plan for methane-, H₂- and electricity-infrastructure in HIC Rotterdam.
3. The development of a multi-model tool that is aimed at a better understanding of the performance of integrated investment plans for energy infrastructure (methane, H₂ and electricity) in HIC Rotterdam in many scenarios. This tool should also be re-usable in potential future projects, such as a project aimed at the national main grids.
4. The execution of a stakeholder dialogue with relevant industry organizations to align the design of the scenario space.
5. The development of interactive visualizations of the impact of scenario storylines on overload patterns during the planning horizon for the H₂- and 380 kV-networks with the following added value:
 - a. Provision of decision support information about the long-term impact of energy infrastructure for decision-making on societally desirable options for the long-term evolution of the energy system.
 - b. A tool that can be used for the design process for the creation of a strategic direction for a robust, adaptive investment path of integrated energy infrastructure.

³ MIEK investment path: the approved investment path for electricity, methane and H₂-infrastructure for HIC Rotterdam for the period up to and including 2030 that is part of the Dutch Multi-year program Infrastructure, Energy and Climate in the Netherlands (*Meerjarenprogramma Infrastructuur, Energie en Klimaat*)

For dissemination of the project results, the final project objectives were agreed upon:

6. Public dissemination of the developed method and (software)tools.
7. Active dissemination of developed knowledge and insights with relevant stakeholders.

The addressed research questions and project objectives slightly differ from the formulated research questions and project objectives at the start of the project (see appendix A for more details about the evolution of the project focus).

1.3 Scope of work of case study

For the development of the Gridmaster method, the case study HIC Rotterdam has been used. Below the scope of work is described.

1.3.1. Geographical system boundaries

Figures 1 - 3 show the geographical system boundaries of the project.

1.3.2. Modeling scope

Table 1 highlights the modeling scope of work of the project.



Figure 1: geographical systems boundary of the considered electricity networks



IN SCOPE:

- 1) all H-pipelines inside the frame (all red pipelines and two green pipelines between Vondelingenplaat and Europoort/Maasvlakte)
- 2) Blending station Pernis
- 3) High pressure low calorific gas pipeline inside the frame
- 4) New high pressure H₂-infrastructure inside the frame (except H₂-infrastructure needed for the H-vision project)

Figure 2: geographical system boundary of the considered methane- and H₂-networks

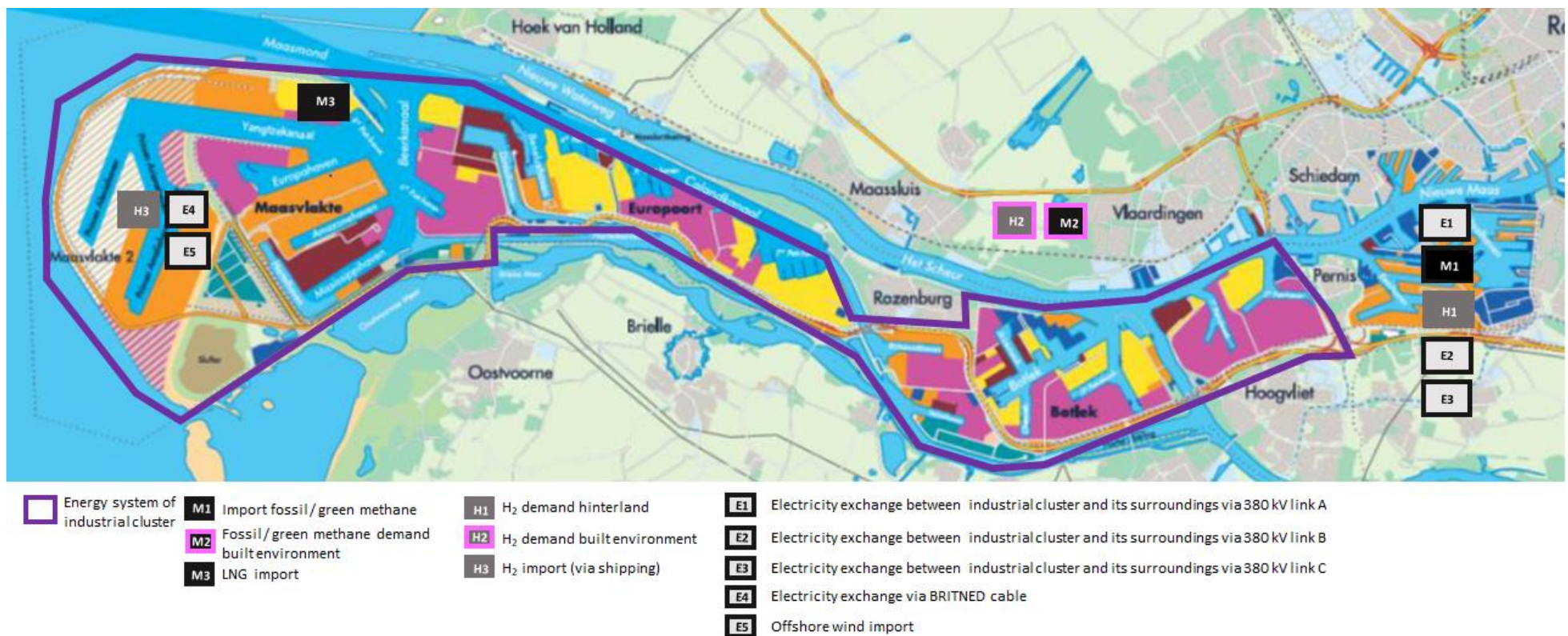


Figure 3: geographical system boundary of the considered industrial cluster

Table 1: modeling scope of work

Scope item	Specification
Planning horizon	2022 (current year) – 2050
Considered reference years in planning horizon	2025, 2030, 2035, 2040, 2045 and 2050
Considered energy infrastructure	Infrastructure for transport of electricity (380 kV, 150 kV and Medium Voltage connection points (25 kV, 50 kV and 66 kV), H ₂ and methane. The currently commercially operated H ₂ -infrastructure for H ₂ supply to oil refineries is out of scope. The potentially new H ₂ -infrastructure for blue H ₂ -transport after realization of the H-vision project is also out of scope. Other (potential) energy networks, like a CO ₂ - or heat network are also out of scope.
Time scale of operational model for energy system state determination during a reference year	Hourly (during 8760 hours of a reference year the energy system state is determined)
Data input scenario space model	<p><u>In scope:</u></p> <ul style="list-style-type: none"> - Used dataset in 'Windmaster project' as basis [4] - Update of data for synthetic fuel and synthetic methanol production technologies - Incorporation of data from the public Wuppertal report, published in 2016, on decarbonization pathways for the industrial cluster of the Port of Rotterdam [6] - Potential additions resulting from a stakeholder dialogue about a preliminary scenario space design - Potential uncertainty options about the evolution of the electricity market model <p><u>Out of scope:</u></p> <ul style="list-style-type: none"> - Exhaustive options for potential structural change of energy conversion assets for the oil refinery and petrochemical cluster - Road and rail mobility change options that potentially impact the considered energy infrastructure - Structural change options for terminals and tank storage facilities that potentially impact the considered energy infrastructure. - Potential flexibility measures / assets like energy storages and demand site management rules
Data input energy infrastructure	Level of detail for the energy infrastructure is comparable with the used energy infrastructure topology in the 'Windmaster project' [4]

1.4 Structure of report

The remainder of the report is organized as follows. Section 2 provides the theoretical foundations the designed Gridmaster method has been based on. Section 3 highlights the Gridmaster method. In section 4 the case study is introduced. Section 5 covers the development of the scenario space and coherent energy system model in the case study. Section 6 illustrates the selection of desirable “storylines” in the case study. The development of a strategic direction for a robust, adaptive investment path within the case study is described in section 7. The results of the project are discussed in section 8. In section 9 conclusions are drawn and finally recommendations for future work are given in section 10.

2.Theoretical foundations

In this section the theoretical foundations for the developed Gridmaster method is described. This section is integrally adopted out of [5].

A growing body of literature is emerging about approaches and tooling that supports decision-making under deep uncertainty. In the water management sector, these approaches are already applied in real decision-making processes. For example, in the Netherlands, the central government, water authorities, provinces and municipalities are working together on a new Delta Program on Flood Risk Management and Fresh Water Supply in which a new, adaptive management concept is applied: the Adaptive Delta Management approach [7]. The strategic investment planning challenge for integrated energy infrastructure is analogous to the investment planning challenge that is addressed in the Delta Program: decision-making on large capital investments in a context of deep uncertainty about how the future requirements for infrastructure will unfold.

Like the applied approaches in the water management sector, the Gridmaster method uses basic principles from a new strategic planning paradigm known as ‘decision-making under deep uncertainty’. Three key ideas underpin this new paradigm [3]: (i) exploratory modeling; (ii) adaptive planning; and (iii) decision support. The first key idea, exploratory modeling, is a research method that uses simulation for analyzing complex and uncertain systems [8,9]. In this method, the aim is to systematically explore the consequences of various uncertainties that affect the system of interest. In fact, many simulations for the exploration of ‘what-if’ scenarios are conducted in which the values for uncertain factors as well as policy alternatives can be varied. Subsequent analysis of simulation results enables insights in patterns of system behavior over the entire uncertainty space [9]. The second key idea, adaptive planning, means that plans are designed from the outset to be adapted over time in response to how the future may actually unfold. Having an adaptive plan allows decisionmakers to adapt the implementation of this plan to the actual unfolding of the future [3]. The third key idea that underpins decision-making under deep uncertainty is decision support. Decision-making on complex and uncertain systems generally involves multiple actors coming to an agreement. In such a situation, decision-making requires an iterative approach that facilitates learning across alternative framings of the problem, and learning about stakeholder preferences and trade-offs, in a collaborative process of discovering what is possible [10]. Under deep uncertainty, decision support should aim at enabling deliberation and joint ‘sensemaking’ among the various parties to a decision [3]. Figure 4 summarizes the coherence between these key ideas. Exploratory modeling leads to options for adaptive plans that are input for decision support in which these options are evaluated in a multi-stakeholder process. In turn, this process step can lead to a new exploratory modeling process step with potential altered uncertainties and valuation of the outcomes of interest.

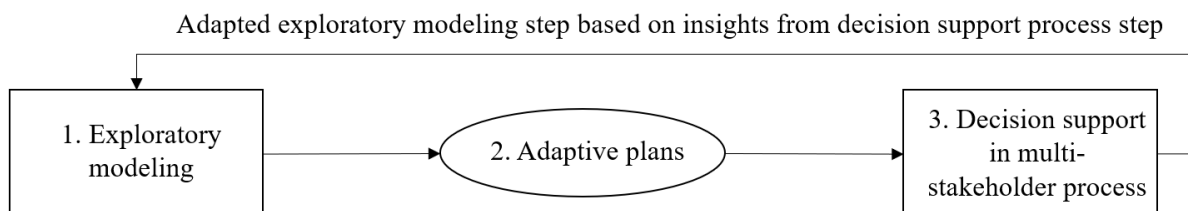


Figure 4: Relation between the key ideas underpinning decision-making under deep uncertainty

Various methods for decision support on strategic planning under deep uncertainty draw on these key ideas, such as Robust Decision Making (RDM), Dynamic Adaptive Planning, Dynamic Adaptive Policy Pathways, Info-

Gap Decision Theory, Engineering Options Analysis and variants thereof (see for example [11-16]). Given the nature of the decision problem, combinations from elements of these methods should be chosen to best support the decision problem at hand. Using the taxonomy proposed in [3], it was decided to use RDM as the base method for the development of the Gridmaster method.

RDM rests on a simple concept. Rather than using computer models and data as predictive tools, the approach runs models myriad times to stress test proposed policy decisions against a wide range of plausible futures [1, 2]. By using visualization and statistical analysis of the resulting large dataset of simulation results, key features can be identified that distinguish those futures in which plans meet and miss their goals. This information helps decisionmakers to identify and frame difficult trade-offs. Furthermore, it supports the evaluation of alternative policies and the decision-making process on robust policies. Those policies lead to the most effective trade-off in meeting multiple objectives over many scenarios.

Under conditions of deep uncertainty, it is necessary to measure the performance of a plan across a wide range of scenarios, rather than measuring the performance of the plan in a 'best guess future' [17]. In the context of many plausible scenarios, application of robustness measures based on the concept of 'satisficing' (a portmanteau of *satisfy* and *suffice*) appears to be most appropriate. Satisficing expresses the extent to which the performance of a solution remains acceptable in many scenarios, without necessarily being the optimal solution [17]. For expressing the satisficing robustness of plans, the domain criterion is one indicator which can be used. This criterion quantifies the volume of the scenario space in which a solution meets the decisionmaker's performance thresholds. In practice, this is done by calculating the fraction of sampled scenarios in which a solution satisfies one or more performance thresholds [17].

For the exploratory modeling step in the RDM approach, a simulation model is needed that simulates the evolution of capacity bottlenecks in energy infrastructure given an investment path and a scenario. A scenario describes a possible evolution of structural changes of conversion assets, energy import and energy export in various geographic locations over time. Moreover, a scenario encompasses the operational behavior of the envisioned future energy system in the reference years of a scenario. Given the challenge to develop a representative simulation model, a multi-model design is preferable. In this multi-model, existing sub models that describe certain parts of the energy system can be used. Each sub model is developed by the stakeholder that has the most knowledge of and expertise in the system represented by that model. The development of the multi-model is a collective effort, creating a basis for transparency and confidence in the results and avoiding the creation of a 'black box' model, whose results can be difficult to interpret and trust.

The development and realization of the multi-model can be labeled as a form of 'participatory multi-modeling'. In participatory multi-modeling, model developers and stakeholders cooperate to increase mutual knowledge transfer and support enhanced learning about the system of interest. By this practice social learning is encouraged and new insights for participating stakeholders arise due to the interaction with other stakeholders [18]. The participatory process of modeling can serve as a leveraging point by facilitating social learning amongst stakeholders [19]. Next to the social learning amongst the model developers, social learning between the grid operators and stakeholders is enabled by the participatory character of the developed modeling practice in the Gridmaster project.

3. Gridmaster method

In figure 5 the developed Gridmaster method is highlighted. This method has been partially tested in the case study Gridmaster HIC Rotterdam (see section 4). The Gridmaster method serves as alternative for the current long-term grid planning method in which three to four scenario (cornerstone) points represent the uncertainty space for long-term network planning at individual grid operators. The result of the Gridmaster process is a strategic direction for a robust, adaptive integral investment plan. This result serves as input for the development of strategic robust adaptive investment plans at the individual grid operators.

A process step within the Gridmaster method is executed by either the group “collective grid operators” or by the group of “all relevant stakeholders”. The group “collective grid operators” owns the considered energy infrastructure for which strategic investment planning is conducted. The group “all relevant stakeholders” comprise all stakeholders that are affected by the evolution of the energy system. The group “collective grid operators” is part of the group “all relevant stakeholders”.

The method can be divided into four parts:

1. The development of the scenario space and a coherent energy system multi-model
2. The selection of socially desirable storylines of energy system evolution pathways
3. The development of a strategic direction for a robust, adaptive investment path
4. The monitoring of the development of the energy system

Part of the description of Gridmaster process steps is adopted from [5].

3.1. Development of the scenario space and a coherent energy system multi-model

Figure 6 shows the process steps within the part of the Gridmaster method in which the scenario space and a coherent energy system multi-model are developed. These process steps are shortly described below.

Step 1A1. System description. In this step the system boundaries of the considered energy system are described. This description entails the geographic area, the types of energy subsystems and the considered energy infrastructure. Furthermore, the time horizon of the analysis must be set.

Step 1A2. Framing decision-making. In this step the decision problem is structured via the **XLRM** framework [11]: **X** stands for the external factors, the factors that cannot be controlled by the decisionmaker; **L** stands for policy Levers, the factors that can be controlled by the decisionmaker; **R** represents the relationships inside the considered system; and **M** stands for Metrics, the indicators that are used to measure the performance of a specific policy. For investment planning of integrated energy infrastructure, independent external factors (**X**) represent specific uncertainties with respect to the potential evolution of an energy subsystem under consideration, excluding the energy infrastructure. A single scenario is generated by a specific combination of selected values for the defined external factors. Such a scenario comprises the evolution of the energy system in six consecutive reference years, namely 2025, 2030, 2035, 2040, 2045 and 2050.

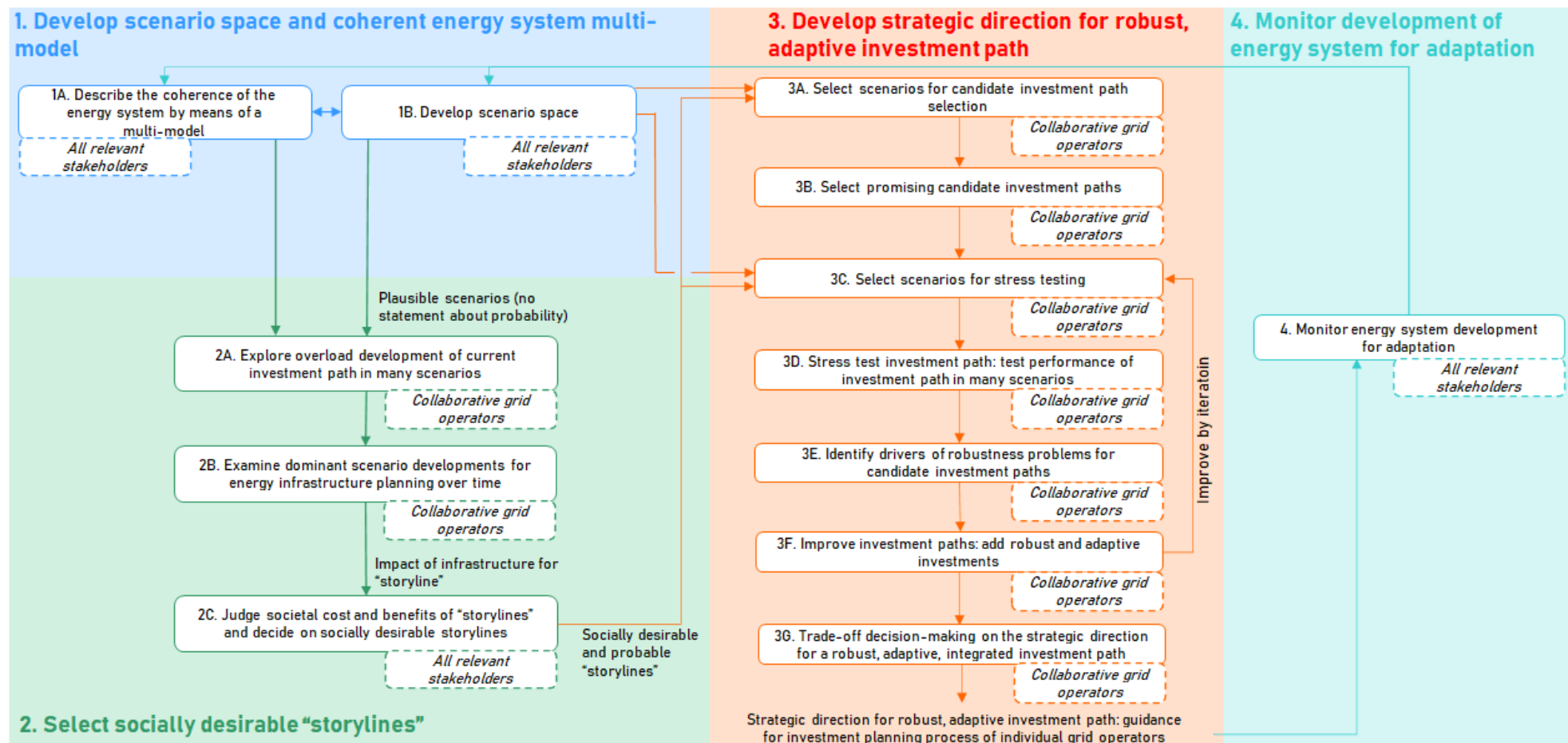


Figure 5: developed Gridmaster method

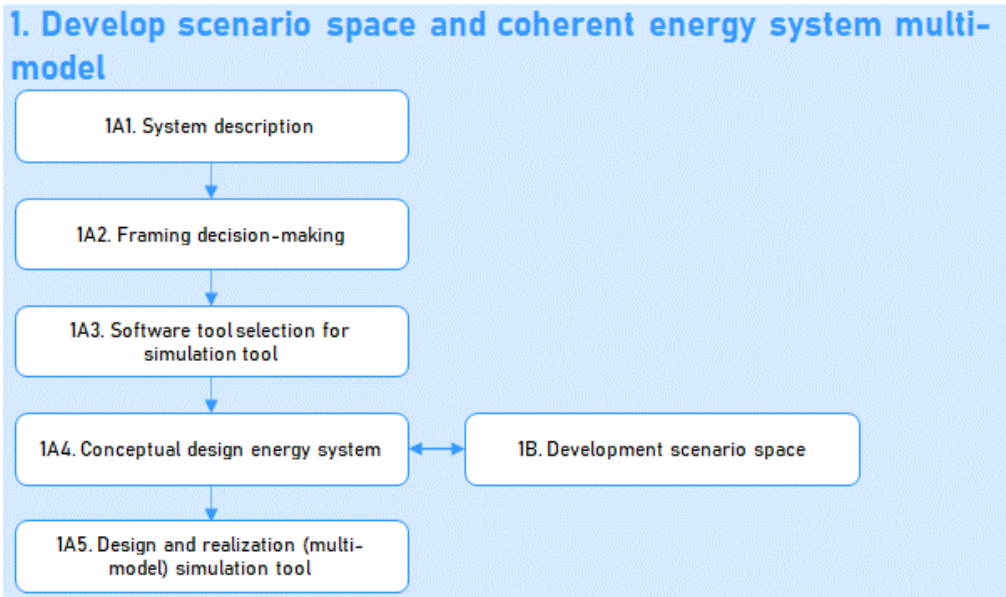


Figure 6: process steps for the development of the scenario space and a coherent energy system model within the Gridmaster method

The levers (**L**) comprise investment paths for the considered integrated energy infrastructure. An investment path comprises: (1) realized fixed investment packages in specific reference years in the period from now till 2050, (2) rule-based investments representing a certain investment philosophy based on the rated capacity of connected customer sites to an infrastructure node and a threshold value thereof, and (3) rule-based adaptive investments that are implemented depending on specific scenario events (triggers or adaptation tipping points) which lead to a sharp increase in the required transport capacity. Investment paths can be translated to an investment plan by taking investment realization times into account.

The relationships (**R**) inside the considered system are represented within a simulation model. The model enables the execution of simulations in which system behavior can be explored for specific combinations of scenarios and investment paths. The relations, in a simple sense, can be interpreted as a set of equations and algorithms that transform the input (external factors and levers) to outcomes.

Metrics (**M**) are chosen to summarize information from the simulation results for decision support purposes. A first group of metrics is defined for the indication of the impact of energy infrastructure on long-term options for the energy system evolution. A second group of metrics is defined for the expression of the performance of the investment path across many scenarios. The applied metrics in the case study will be discussed in section 5.

Step 1A3. Software tool selection for simulation tool. The specification of modeling tools that will be used to design the multi-model simulation tool are specified in this step.

Step 1A4. Conceptual design energy system. In this step the current energy system is described. Furthermore, options for investment paths and the interaction between an investment path and developments of the energy system are defined. The potential developments of the energy system are encompassed in the scenario space (see step 1B).

An initial set of investment paths is developed in workshops with grid strategists. These investment paths serve as input for process step 3B in which candidate investment paths are selected.

Figure 7 summarizes the structuring of the decision problem in the developed method.

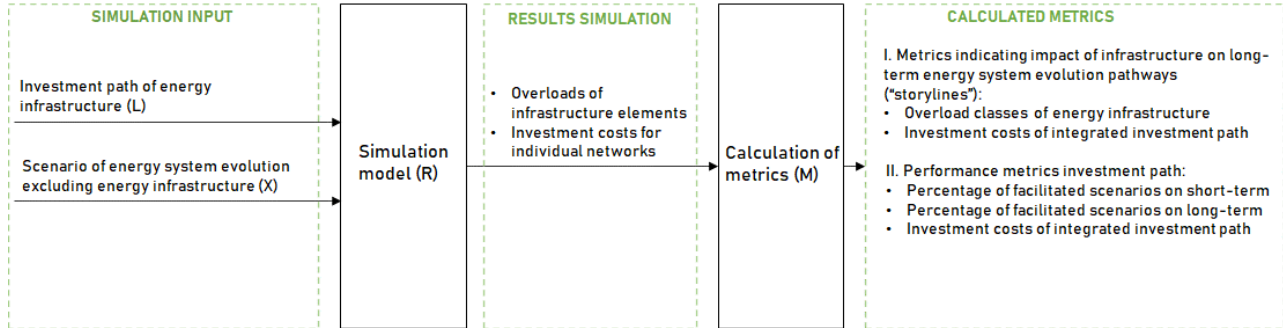


Figure 7: Overview of the XLRM structured decision problem in the Gridmaster method

In a reference year within a scenario, a particular set of conversion assets is present in the considered geographic area. Furthermore, a particular energy exchange situation between the area and its surroundings exists. Finally, the settings for particular operational characteristics of the energy system are part of a scenario. Every scenario exhibits a specific evolution of transport capacity requirements for electricity, hydrogen, and methane, resulting in overload patterns over time for the considered energy networks. Furthermore, per scenario an investment cost pattern over time will arise in case scenario dependent investment rules are part of the investment path. Based on the outputs of the simulation model, metrics are calculated that provide information about I) the impact of energy infrastructure on long-term energy system evolution pathways ("storylines") and II) the performance of the investment path across many scenarios.

Step 1A5. Design and realization of multi-model simulation tool. Based on the defined metrics and conceptual design of the energy system, the multi-model simulation tool is designed and realized in this step. The individual grid operators contribute to the realization of the simulation tool by providing load flow models that are capable to calculate overload values for infrastructure elements that are part of their owned networks. These load flow models are integrated into the multi-model simulation tool. The developed multi-model simulation tool in the case study is discussed in section 5.

Step 1B. Development of scenario space. The scenario space is constructed from independent external factors that govern a certain potential structural or operational evolution of a subsystem within the considered energy system. Each external factor has various values that represent a different evolution of the energy subsystem. A unique combination of values for the external factors yields a scenario.

Two classes of external factors (uncertainties) are defined to represent the deep uncertainty for investment planning of integrated energy infrastructure. The first class comprises uncertainties with respect to structural change of the energy system. Structural change relates to a change of the installed base of conversion assets in the considered geographical area or to changing trends in energy exchange between the geographical area and its surroundings. For example, the growth of offshore wind landing capacity in the considered geographical area over the next 30 years might be defined as an external factor. Values for this external parameter refer to

different growth scenarios. Growth scenarios for hydrogen transit demand, technology changes at industrial sites, and growth scenarios for the integration of new production plants are other examples of defined external factors in the case study. The second class of uncertainties relates to the uncertainty about how the future energy system might be operated. The merit order for power generation assets is an example of this kind of uncertainty. Different merit orders lead to different operations of individual power generation assets inside the geographical area and thus to different operations characteristics of the energy system.

A stakeholder dialogue to gather information about future visions of energy system evolution is part of the design process of the scenario space. Since the method is based on the exploration of many scenarios, relevant scenarios for stakeholders can be incorporated into the scenario space.

3.2. Selection of socially desirable “storylines”

After the development of the scenario space and a coherent energy system model, process steps are executed that lead to the selection of socially desirable “storylines”. Below these steps are elaborated on.

2A. Exploration of overload development of current investment path in many scenarios. The first step for getting insight into social desirable “storylines” about energy system evolution pathways is to explore the overload patterns for the considered energy infrastructure that arise during the planning horizon in many scenarios of energy system development in case the current investment path is executed. To this end, many scenarios are selected from the scenario space. This is done via Latin Hypercube Sampling that produces a sample of the scenario space that reflects the true underlying distribution and it tends to require much smaller sample sizes than simple random sampling [20]. Simulation of the system development for the current investment path of energy infrastructure in the set of selected scenarios yield overload patterns over time for the considered energy infrastructure. These overload patterns serve as basis data for the next step.

2B. Examination of dominant scenario developments for energy infrastructure planning over time. Identification of the external factors in scenarios that have the most prominent impact on the evolution of overload magnitudes of the considered energy infrastructure is the aim of this step. This set of external factors, which is a subset of the set of external factors the scenario space was constructed from, is used to build storylines of scenarios. A storyline represents a potential main direction of the evolution of the energy system that impacts the overload pattern of energy infrastructure in a significant way. It comprises a set of scenarios with similar characteristics. Subsequently, per storyline, the overload evolution of the energy networks and individual infrastructure elements can be shown. This information serves to support the stakeholder dialogue in step 2C. For the identification of drivers of overload patterns the Patient Rule Induction Method (PRIM) is used on the dataset that is obtained from step 2A. (see section 6 for more details on PRIM).

Step 2C. Social dialogue for determination of socially desirable storylines. Informed by the storyline – overload relations yielded from step 2B, in step 2C a social dialogue is conducted aimed at the determination of the long-term ambition for the energy system evolution. In this step the cost and benefits of storylines for scenarios are evaluated. A storyline represents potential social benefits. For example, the growth of synthetic fuel production capacity in an industrial cluster, that might be part of a storyline, has social benefits due to resulting

employment in that area. On the other hand, facilitation of this storyline incurs social costs in the form of required investments in energy infrastructure and the potential impact on land use for energy infrastructure expansion. These costs are expressed via metrics that indicate the impact of infrastructure on long-term energy system evolution pathways (see section 5). Based on the cost – benefit evaluation of storylines a decision can be made about the long-term ambition for the energy system evolution. This decision potentially restricts the uncertainty for energy infrastructure investment planning by consciously excluding potential storylines that in the long-term should be facilitated by the energy infrastructure. In step 2C, it should be strived for that all relevant stakeholders are involved in the decision-making process on determining the long-term energy system ambition.

3.3. Development of strategic direction for a robust, adaptive investment path

Step 3A. Selection of scenarios for the selection of candidate investment paths. A selected set of scenarios from the scenario space that is used for the identification of candidate investment paths, is the aim of this step. Two important inputs for this selection are necessary. First, the information about which storylines are socially desirable, resulting from step 2C, is an input. Only socially desirable storylines should be taken into account for investment planning of energy infrastructure. Secondly, a consideration of likelihood of storylines that become reality in the future is valuable. Based on these inputs, a selection of scenarios is made from the scenario space that serves as a representation of the deep uncertainty that investment plans for energy infrastructure should cope with. The selected set of scenarios is used in step 3B of the Gridmaster method.

Step 3B. Selection of promising candidate investment paths. The objective of this step is to select the most promising investment paths (so-called candidate investment paths) from the developed set of initial investment paths (developed in step 1A4). Based on a comparison of the computed robustness metrics for the investment paths a trade-off decision is made between the robustness performance to facilitate scenarios across a broad range of scenarios and other performance indicators like investment costs. A selected candidate investment path serves as a good starting point for the development of a strategic direction for a robust, adaptive investment path for energy infrastructure.

Step 3C. Selection of scenarios for stress testing of candidate investment paths. In this step the set of scenarios is selected from the scenario space for the stress testing of the candidate investment paths in step 3D. This set is based on input about the probability of socially desirable storylines (see also step 3A).

Step 3D. Stress testing of candidate investment paths. In this step the performance of candidate investment paths is evaluated by stress testing. Many scenarios (9,980 in the executed case study within the project), sampled from the scenario space, are used to evaluate the robustness performance of a candidate investment path. In this evaluation, the percentage of scenarios that can be facilitated by the investment path is determined. Additionally, the investment costs of an investment path is determined.

Step 3E. Identification of drivers of robustness problems for candidate investment paths. Identification of the external factors that have the most prominent impact on the evolution of overload conditions for the considered energy infrastructure for a candidate investment path is the aim of this step. This set of external

factors, which is a subset of the set of external factors the scenario space was constructed from, is used to build storylines of scenarios. This step is similar to step 2B. In contrast to stress testing of the current investment path, candidate investment paths are stress tested in a set of scenarios that differs from the set of scenarios that is used in step 2B. The resulting storyline-overload relations serve as information for the development of a strategic direction for a robust, adaptive investment path (obtained by the conduction of the subsequent process steps).

Step 3F. Improvement of investment path: add robust and adaptive investments. In this step, candidate investment paths are improved by iterative stress testing. The developed storyline – overload relations, created in step 3E, serve as input for the expert design process to find potential solutions for future overload conditions. Potential solutions for improvement of the investment path comprise both robust investments and adaptive investments. Robust investments are planned to improve the short-term robustness of the investment path. These investments are chosen in such a way that the utilization of these assets is acceptable across a broad range of storylines. On the other hand, adaptive investments are effective in case specific storylines emerge. Trigger conditions should be defined to timely initiate a certain package of adaptive investments.

The identified promising improvements of the investment path are subsequently integrated in the original investment path. Hereafter, these upgraded investment paths are stress tested across a broad range of scenarios. Evaluation of the stress test results yields robustness performances of the alternative investment paths.

Step 3G. Trade-off decision-making on the strategic direction for a robust, adaptive integrated investment path. In a sensemaking process the created investment paths are compared and the most effective investment path is chosen. Although the decision-making responsibility for investment planning of individual networks lies at the individual grid operator, in an ideal situation, the decision-making by the individual grid operators is aligned in order to obtain a coordinated strategic direction for a robust, adaptive integrated investment path.

In case the robustness performance of the most effective investment path is considered unsatisfactory, this investment path is stress tested again (iteration loop that starts at step 3C). This stress test and trade-off decision-making loop is continued until a satisfactory robustness performance is obtained. The resulting investment path gives a strategic direction for a robust, adaptive integrated investment path. This serves as the starting point for the development of a detailed robust, adaptive investment plan for an individual energy network that is part of the considered integrated energy infrastructure. The development of this plan is conducted by the individual grid operator.

3.4. Monitoring the development of the energy system for adaptation

After the decision on the strategic direction for a robust, adaptive integrated investment path, it is necessary to monitor the energy system evolution (step 4 in figure 5). This monitoring can trigger a new initiation of the execution of the Gridmaster method. A reason for this new initiation is a significant alteration of the real uncertainties about the energy system evolution. This can be, for example, caused by decisions that lead to path dependencies in the energy system evolution under consideration. For example, for the HIC Rotterdam, a

final decision on Carbon Capture and Storage (CCS), will lead to such a situation. Such a decision will block certain storylines on energy system evolution that are currently still plausible.

4. Case study description

In the case study, the developed Gridmaster method has been partially tested and developed. Not all process steps have been tested due to scope limitations of the project. Table 2 provides an overview of the process steps that have been tested in the case study during the project.

In section 5 the scenario space and linked coherent energy system model, developed in the case study is described. Section 6 elaborates on the executed process steps in the case study to select socially desirable storylines of energy system evolution pathways. In section 7 several process steps for the development of a strategic direction for a robust, adaptive investment path, tested in the case study are highlighted.

Table 2: overview of tested process steps of the Gridmaster method in the case study

Process step	Description of scope of tested process step in case study
1A. Description coherence of energy system by multi-model	All networks included in the energy system multi-model
1B. Development of scenario space	Scenario space linked to all networks
2A. Exploration overload development current investment path in many scenarios	All networks included, MIEK investment path used as current investment path
2B. Examination of dominant scenario developments for overload evolution over time	Executed for the 380 kV- and H ₂ -networks
2C. Decision-making on socially desirable storylines	Not executed
3A., 3B. Selection of promising candidate investment paths	Not executed
3C., 3D., 3E. Stress testing candidate investment path including identification of scenario drivers for robustness problems of this investment path	- Executed for the 380 kV, H ₂ - and MV-network
3F. Improvement of candidate investment path	- Analysis executed for the MV-network - Explorative analysis executed for the 380 kV- and H ₂ -network
3G. Trade-off decision-making on strategic direction for robust, adaptive investment path	Not executed
4. Monitoring of energy system development for adaptation	Not executed

5. Development of scenario space and coherent energy system model

5.1 Scenario space design (X)

5.1.1 Objective

The objective of the design of a scenario space is threefold. First, it should enable the exploration of overload development for the considered energy infrastructure of the current investment path. This provides necessary data for the creation of insight into the impact of energy infrastructure on various potential storylines for the long-term evolution of the energy system. Secondly, the scenario space should enable the stress testing of an investment path across a broad range of scenarios. In the third place, the design should be capable to include scenarios that have been put forward by stakeholders of the grid operators. This is required for coordinated decision-making on socially desirable storylines and for social support of the to be developed strategic direction for a robust, adaptive investment path for energy infrastructure.

Scenarios that are part of the scenario space represent a possible evolution of the energy system in the period from 2022 – 2050 that is relevant for long-term investment planning of the energy infrastructure. By application of a sampling method sets of scenarios can be generated from the scenario space that represent the uncertainty the planning of energy infrastructure should deal with. The sampling method is the way how scenarios are selected from the scenario space.

5.1.2 General starting points

In the development of the scenario space the following general starting points have been used as a guidance:

1. The scenario space should include diverse plausible scenarios that individually show a certain energy system evolution over the planning horizon. Every scenario within the scenario space starts with the current energy system situation and has a unique evolution of the energy system over time.
2. The scenario space is constructed from external factors. An external factor represents an uncertainty parameter affecting the evolution of the considered energy system. A value for this external factor drives a particular evolution of a part of the considered energy system.
3. The values for external factors should be independently combinable⁴.
4. A single scenario is generated by the selection of a single value for all external factors the scenario space is built from.
5. Relatively few values for a single external factor should be used to prevent that an unnecessary large scenario set is required for the analysis about the drivers for the performance of an investment path. The larger the necessary size of this scenario set, the more simulation runs should be carried out resulting in higher computational costs and lead times.

⁴ Dependent developments in scenarios have been taken into account by 1) describing of interdependent scenario developments over time via a single value of an external factor or by 2) simulation of the system emergence over time via rules (e.g. the dependency of new technology integration on the available free spatial area or the chain reaction rules for the closure of the chlorine cluster in case a certain threshold for minimum chlorine demand is reached).

5.1.3 Scenario space foundations for case study

In this paragraph the main features of the developed scenario space for the case study have been described. More details about the developed scenario space can be found in appendix B.

Classes of uncertainty

In the case study two classes of uncertainties are defined to represent the deep uncertainty for investment planning of integrated energy infrastructure. The first class comprises uncertainties with respect to structural change of the energy system. Structural change relates to a change of the installed base of conversion assets in the industrial cluster or to changing trends in energy exchange between the industrial cluster and its surroundings. For example, the growth of offshore wind landing capacity over the next 30 years is defined as an external factor. Values for this external parameter refer to different growth scenarios. Growth scenarios for hydrogen transit demand and technology changes at oil refinery sites are other examples of defined external factors in the case study. The second class of uncertainties relates to the uncertainty about how the future energy system might be operated. The merit order for power generation assets is an example of this kind of uncertainty. Different merit orders lead to different operations of individual power generation assets inside the industrial cluster and thus to different operations characteristics of the energy system.

Division into subsystems and location of conversion assets

The energy system of the HIC Rotterdam can be divided into various subsystems. A subsystem comprises a group of energy conversion assets for which it is assumed that structural change is driven by similar factors. In addition, a specific energy supply or demand development can also be regarded as a subsystem within the energy system of the HIC Rotterdam. For example, a potential phasing out of oil refineries, a certain class of conversion assets, will be amongst others dependent on global oil market developments. Furthermore, the potential implementation of a central system as CCS will lead to CO₂ sequestration of several oil refinery plants in the HIC Rotterdam. Therefore, the oil refinery sites are considered as a subsystem within the scenario space of the HIC Rotterdam. The H₂ demand to the hinterland is another example of a subsystem that is part of the energy system of the HIC Rotterdam.

Per subsystem, potential structural change pathways of the considered subsystem have been envisioned. The choice of subsystems has been done in such a way that the potential structural change in a particular subsystem is independent of the potential structural change in the other subsystems. As a result, a scenario for structural change of the whole HIC Rotterdam energy system over the planning horizon can be composed of the scenarios for structural change for its defined subsystems.

Apart from the subsystems that are subject to structural change during the planning horizon, the Dutch electricity market is also a subsystem that is affecting the energy system of the HIC Rotterdam. The electricity market conditions drive the operation of certain conversion assets like hybrid boilers or (repowered) fossil methane power plants during a reference year of a scenario. As a consequence, the electricity exchange between the HIC Rotterdam and its surroundings is affected by the electricity market.

Table 3 shows the chosen subsystems the energy system of the HIC Rotterdam has been divided into (see appendix C for more details about the motivation thereof).

For the modeling of a relevant scenario space for investment planning of energy infrastructure, the geographic location of energy conversion assets and locations for the energy exchange between the HIC Rotterdam and its surroundings is relevant. Therefore, geographic sites have been defined at which conversion assets can be located or at which energy carrier exchange between the HIC Rotterdam and its surroundings can take place.

Conversion assets that are currently part of the same subsystem might be physically located in different geographic areas within the HIC. Figure 8 shows the allocation of the current sites within the HIC Rotterdam to the defined subsystems.

An assumption in the developed scenario space is that the area of a site remains constant during the planning horizon within and across scenarios. This is relevant since in the scenario space model, the integration of new production technologies at sites is restricted by the available space for the installation of these technologies. An exception is the Maasvlakte 2 area that will become available for non-oil based hydrocarbon fuel and chemical feedstock production. The available area during the planning horizon for this site is taken as uncertainty. As a consequence, across scenarios the available area for Maasvlakte 2 for the growth of non-oil based hydrocarbon fuel and chemical feedstock plants will vary.

Land use policy

Another important assumption in the designed scenario space is that the sites remain part of the same subsystem during the considered planning horizon. This means, for example, that a current oil refinery site remains part of the subsystem 'oil based and non-oil based hydrocarbon production and (repowered) coal fired power plants' in all scenarios. At this site, only structural changes are possible that are related to the uncertainty that is considered for the subsystem it is part of. A potential shift in site allocation to another subsystem is excluded in the current set up of the scenario space design. This means, for example, that it is assumed that it is impossible that in the future part of a current oil refinery site will be used to install onshore wind or onshore solar PV production capacity.

Furthermore, in the designed scenario space, no options have been implemented that restrict growth of certain new technologies at certain geographic locations in the HIC Rotterdam. For example, a potential land use policy that restricts the integration of water electrolysis capacity at the east side of the HIC Rotterdam is not implemented in the current scenario space. Since the location of capacity growth of conversion assets is relevant for the required transport capacity, the applied land use policy that influences the growth of certain conversion asset types across the geographical area is a relevant factor to be taken into account for the investment planning of energy infrastructure.

Table 3: defined subsystems within the modelled energy system of the HIC Rotterdam

Subsystem	Sites that are part of the subsystem
1. Oil based and non-oil based hydrocarbon production and (repowered) coal fired power plants	<ol style="list-style-type: none"> Current oil refinery sites Current central Steam Methane Reforming (SMR) sites (H₂ production for supply to oil refineries) Current coal fired power plant sites Maasvlakte 2 area that is allocated for non-oil based hydrocarbon production plants
2. Chlorine based chemical cluster, other industrial sites and (repowered) methane based utility production sites	<ol style="list-style-type: none"> Current chlorine based chemical cluster Current industrial sites that are not part of the chlorine based chemical cluster and subsystem 1 Current central methane fired power plant sites and central methane fired cogeneration plant sites
3. Nuclear power plant	<ol style="list-style-type: none"> Envisioned site at Maasvlakte 2
4. Onshore wind production	<ol style="list-style-type: none"> Various sites across the HIC Rotterdam
5. Onshore solar PV production	<ol style="list-style-type: none"> Various sites across the HIC Rotterdam
6. Offshore wind landing capacity	<ol style="list-style-type: none"> Assumed is that the installed wind land capacity is connected to a specific 380 kV station
7. Built environment	<ol style="list-style-type: none"> Current peakshaver site (emergency supply of methane for the built environment in cold weather conditions) Current site location where methane is extracted from the main methane backbone across the HIC Rotterdam for fulfilling the fossil methane demand for the built environment
8. Electrical charging of ships & shorepower	<ol style="list-style-type: none"> (Potential) sites for the electrical charging of ships and / or electrical supply during a ships stay at the quay.
9. H ₂ demand hinterland	<ol style="list-style-type: none"> Site located at the east side of the HIC Rotterdam
10. Dutch electricity market	<ol style="list-style-type: none"> Sites affected by the modelled Dutch electricity market situation: <ul style="list-style-type: none"> Sites with a (repowered) coal fired power plant Sites that are part of the chlorine based value chain comprising (H₂) hybrid boilers and, or furnaces Sites that are part of the group 'industrial other' comprising (H₂) hybrid boilers and, or furnaces Sites with (repowered) fossil methane fired power plants or cogeneration units Site with a potential nuclear power generation plant Sites with onshore wind production Sites with onshore solar PV production Site with offshore landing capacity

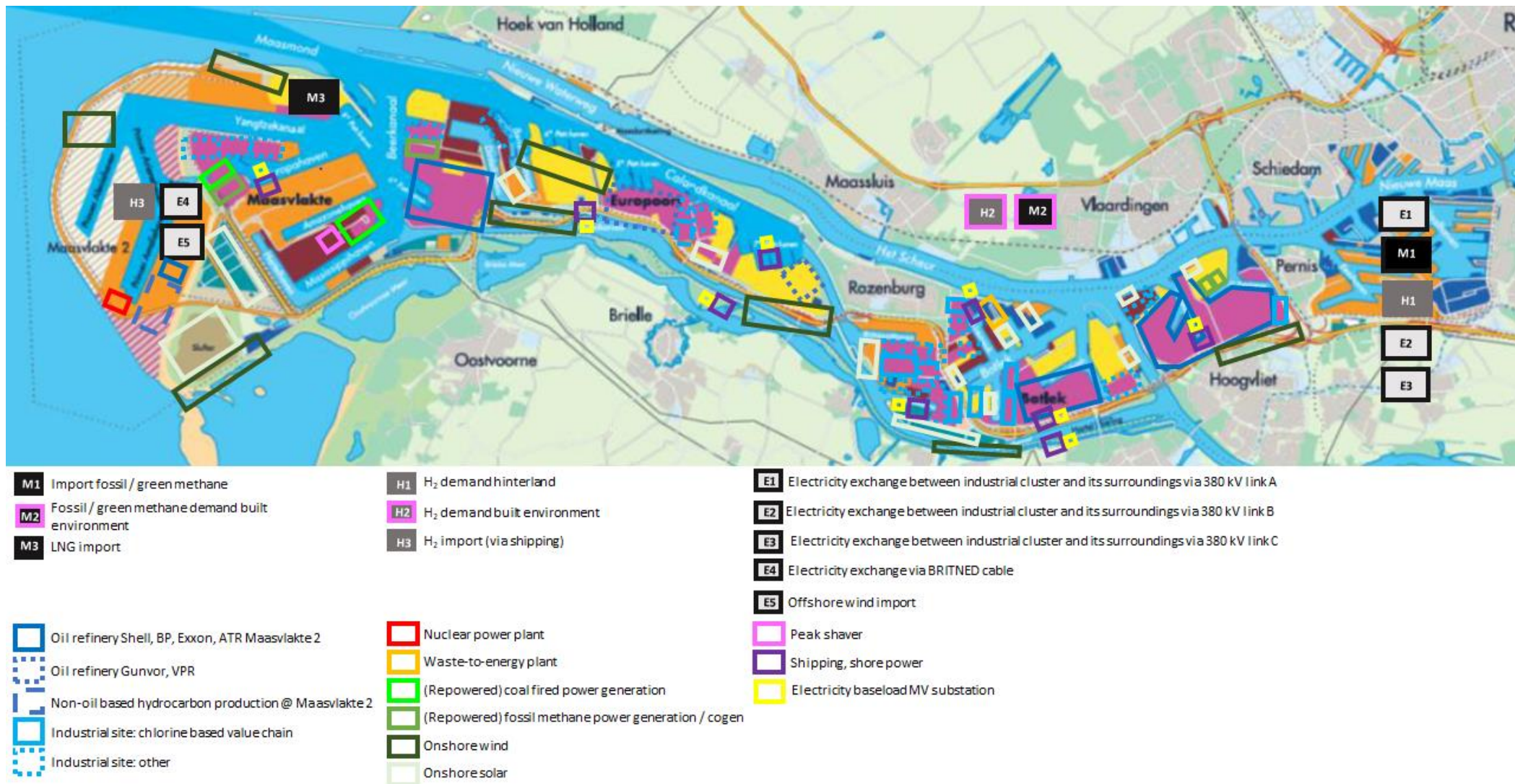


Figure 8: allocation of considered sites to the defined energy subsystems

5.1.4 Developed scenario space case study

Current situation

The current situation is the starting point of every scenario that is part of the scenario space. Per site, the current energy system situation has been described using open source data and estimates. An oil refinery or other industrial site comprises various conversion assets and is connected to the energy infrastructure for exchange of energy carriers. The currently present power generation and cogeneration sites comprise conversion assets for the generation of electricity and steam (in case of cogeneration). These sites are also connected to the energy infrastructure. Also the sites via which energy carrier exchange between the HIC Rotterdam and its surroundings takes place are described. In appendix D the description of the current energy system is highlighted in more detail.

Overview scenario space

Figure 9 shows the developed scenario space for the case study. In total 29 external factors have been defined. Each factor comprises two to eight values, which when combined, in this case leads to 10^{19} plausible scenarios for energy system evolution from now till 2050. In a reference year within a scenario, a particular set of conversion assets is present in the industrial cluster. Furthermore, a particular energy exchange situation between the cluster and its surroundings exists. Finally, the settings for particular operational characteristics are part of a scenario. Every scenario exhibits a specific evolution of transport capacity requirements for electricity, hydrogen and methane over the planning horizon.

Structural change

27 external factors govern the potential structural change of the energy system over time (factors marked with a color in figure 9). Factors that are marked with the same color impact structural change of the same energy subsystem. Below, per subsystem, the external factors will be briefly discussed. In this discussion, figure 9 can be used for reference.

Subsystem 1. Oil based and non-oil based hydrocarbon production and (repowered) coal fired power plants

External factor 0 describes various plausible scenarios for structural change across the planning horizon for the evolution of fossil oil refining conversion assets at the existing Shell, BP and Exxon sites and for structural change options for the current coal fired power plants. Structural change of the currently installed SMRs that are not part of these oil refinery sites, is also part of the scenarios described by external factor 0.

In the future, part of the CO₂ emission sources from the current oil refineries and related SMRs might be captured for permanent storage (CCS). Moreover, a new Auto Thermal Reformer plant (ATR), producing blue hydrogen based on refinery gasses from oil refineries might become operational in case a H-vision project is realized [21].

The future repowering options for the current coal fired power plants are dependent whether or not H-vision will be implemented. In case a H-vision project is realized, the produced blue H₂ will be used to partly replace refinery gases as a source for high temperature heat production at refinery sites. Furthermore, a part of this blue H₂ will be used as feedstock for repowered coal power plants that will be partly fired by blue H₂ (H-vision

		Value							
		a	b	c	d	e	f	g	h
External factor	0.CCS technology paths	Non CCS path 1	Non CCS path 2	Non CCS path 3	Non CCS path 4	CCS basis path 1	CCS basis path 2	H-vision path 1	H-vision path 2
	2a.Capacity reduction Gunvor	Closed 2025	Half capacity 2025, closed 2030	Closed 2030	Half capacity 2030, closed 2035				
	3.Capacity reduction VPR	Closed 2025	Half capacity 2025, closed 2030	Closed 2030	Half capacity 2030, closed 2035				
	4.Available area Maasvlakte 2	Low area allocation scenario	Reasonable area allocation scenario	Big area allocation scenario	Very big area allocation scenario				
	5.Naphtha production from green gas	No naphtha production	Low growth scenario	Reasonable growth scenario	Strong growth scenario	Very strong growth scenario			
	6.Synfuel production	No synfuel	Med. synfuel config1 growth	Max. synfuel config1 growth	Med. synfuel config2 growth	Max. synfuel config2 growth	Med. synfuel config3 growth	Max. synfuel config3 growth	
	7.Synthetic methanol production	No synMeOH_olefin	Med. synMeOH_olefin config1 growth	Max. synMeOH_olefin config1 growth	Med. synMeOH_olefin config2 growth	Max. synMeOH_olefin config2 growth	Med. synMeOH_olefin config3 growth	Max. synMeOH_olefin config3 growth	
	8.Biogasification based olefin production	No biogas_olefin	Med. biogas_olefin1 growth	Max. biogas_olefin1 growth					
	9.Plastic waste based olefin production	No plasticgas_olefin	Med. plasticgas_olefin1 growth	Max. plasticgas_olefin1 growth	Med. plasticgas_olefin2 growth	Max. plasticgas_olefin2 growth			
	49.New technology implementation order	Start synfuel; end naphtha	Start naphtha; end synfuel						
	50.Geographical filling order	West to east	Equal	East to west					
	10.Capacity reduction PUR-MDI plant	Plant half capacity 2030, closed 2035	Plant half capacity 2035, closed 2040	Plant half capacity 2040, closed 2045	Plant half capacity 2045, closed 2050	Plant half capacity 2050	No capacity reduction	50% capacity increase 2040	
	11.Capacity reduction PVC plant	Plant half capacity 2025, closed 2030	Plant half capacity 2030, closed 2035	Plant half capacity 2035, closed 2040	Plant half capacity 2040, closed 2045	Plant half capacity 2045, closed 2050	Plant half capacity 2050	No capacity reduction	
	12.Capacity reduction epoxyresin plant	Plant half capacity 2030, closed 2035	Plant half capacity 2035, closed 2040	Plant half capacity 2040, closed 2045	Plant half capacity 2045, closed 2050	Plant half capacity 2050	No capacity reduction		
	13.Capacity reduction TiO2 plant	Plant half capacity 2030, closed 2035	Plant half capacity 2035, closed 2040	Plant half capacity 2040, closed 2045	Plant half capacity 2045, closed 2050	Plant half capacity 2050	No capacity reduction		
	14.Closure date 'other industrial sites'	Median closure year 2035	Median closure year 2040	Median closure year 2045	Median closure year 2050	No closure			
	15.Filling rule 0.5 GWe electrolyzer	No integration of 0.5 GWe H2O electrolyzer plants	Filling of 25% of available area with 0.5 GWe H2O electrolyzer plants	Filling of 50% of available area with 0.5 GWe H2O electrolyzer plants	Filling of 75% of available area with 0.5 GWe H2O electrolyzer plants	Filling of 100% of available area with 0.5 GWe H2O electrolyzer plants			
	16a.Fossil utility production technology paths	Electrification pathway 1	Electrification pathway 2	Electrification pathway 3	H2 pathway 1	H2 pathway 2	H2 pathway 3	Green gas pathway 1	H2 hybrid pathway 1
	51.Short-term MIEK path	No electrification utilities in 2030	Electrification utilities in 2030						
	17.Nuclear power plant Maasvlakte	No nuclear power plant	1.6 GW in 2040	1.6 GW in 2050					
	18.Onshore wind production	Low growth	Reasonable growth	Strong growth	Very strong growth				
	19.Onshore solar PV production	Low growth	Reasonable growth	Strong growth	Very strong growth				
	20.Offshore wind landing capacity	Low growth	Reasonable growth	Strong growth	Very strong growth				
	24.Switch G-gas consumers: type and volume	Switch to green gas high energy	Switch to green gas low	Switch to H2 high energy	Switch to H2 low energy	Switch to alternative high	Switch to alternative low energy		
	25.Switch G-gas consumers: year of switching	2040	2040	2045	2050				
	26.Charge capacity shipping & shore power	Low growth	Reasonable growth	Strong growth	Very strong growth				
	23.H2 demand hinterland	Low growth	Reasonable growth	Strong growth	Very strong growth				
	28.Merit order order	Order: fossil methane --> biomass/greengas-->H2	Order: fossil methane --> H2 --> biomass/greengas	Order: H2--> fossil methane --> biomass/greengas	Order: H2--> biomass/greengas --> fossil methane	Order: biomass/greengas --> fossil methane --> H2	Order: biomass/greengas --> H2 --> fossil methane		
	34.Scenario rest NL	II3050 regional guidance	II3050 international guidance						

Figure 9: developed scenario space in the case study

option modeling is based on [21]). Due to the fact that H-vision leads to structural change at both the affected oil refinery sites and the current coal power plant sites, the structural change options for these sites have been described with a single external factor.

It is assumed that the current oil refineries Gunvor and VPR will not be connected to the CCS-system in case this system will emerge. Furthermore, based on report [22] it is assumed that the capacity for oil refining conversion assets at these sites will be reduced earlier in time compared to the other oil refineries in the HIC Rotterdam. For these reasons, external factors 2a and 3 have been defined apart from external factor 0. These factors describe scenarios for the potential capacity reduction evolution of oil refinery capacities at the Gunvor and VPR site, respectively.

By CCS implementation, the competitive edge of oil refineries and associated SMRs increases compared to a situation in which no CCS is applied. Therefore, in the scenario space a relation has been made between the implementation of CCS at sites and the options for capacity reduction of fossil energy based conversion assets that are located at these sites: in case CCS is applied, it is assumed that the oil refineries and methane based H₂ production plants connected to this system will remain longer in operation compared to the alternative scenarios in which no CCS is applied.

At sites within subsystem 1, new non-oil based hydrocarbon fed conversion assets might be integrated in the future for the production of fuel and chemical feedstock. Site integration of those assets is among others dependent on the available free space at sites that are part of this subsystem. Implementation of CCS might have an impact on the capacity of future installed non-oil based hydrocarbon production plants in the HIC Rotterdam since CCS will probably lead to the longer presence of oil refineries leading to less free spatial area to install new conversion assets for non-oil based hydrocarbon fuel and chemical feedstock production.

A part of the Maasvlakte 2 area will also be available for the future integration of non-oil based hydrocarbon production plants. It is, however, uncertain which part of this area will be available for integration of those plants. To take this uncertainty into account an external factor has been defined that describes various scenarios for the availability of spatial area at the Maasvlakte 2 site to accommodate non-oil based conversion assets for the production of hydrocarbon fuels and chemical feedstock (external factor 4).

In the scenario space it is assumed that integration of new conversion assets for the production of non-oil-based fuel and / or chemical feedstock in the HIC Rotterdam can only take place at sites that are part of subsystem 1. In case sufficient spatial area is available at those sites new technologies might be integrated.

To vary the implementation of new technologies across scenarios two groups of external factors have been defined in the case study:

1. External factors for growth scenarios of specific new technologies in different configurations across the HIC Rotterdam
2. External factors that govern the site locations at which these technologies are implemented

External factors for growth scenarios of specific new technologies

For all considered potential new technologies a specific external factor has been defined that comprises different growth scenarios of conversion asset capacity for several technology configurations across the HIC (external factors 5 - 9). By selection of a value for such an external factor, a specific growth scenario over the planning horizon for the implementation of a certain group of conversion assets is selected. Table 4 depicts the

considered new technologies for non-oil based hydrocarbon fuel and chemical production within the scenario space.

For example, external factor 6 represents the potential uncertainty about the growth of synthetic fuel production capacity in the HIC Rotterdam across the planning horizon. In scenarios in which value a is selected for this factor, a no growth scenario for synthetic fuel production is part of the overall scenario for the HIC Rotterdam. In contrast, selection of value b leads to a medium growth scenario for synthetic fuel production plants with configuration 1. In case of configuration 1 the required H₂ and CO₂ for synthetic fuel production are produced in HIC Rotterdam with dedicated H₂O electrolysis plants and Direct Air Capture (DAC) units, respectively. On the other hand, selection of value e for external factor 6 leads to a maximum growth scenario for synthetic fuel production capacity with configuration 3. Technology configuration 3 is a configuration in which the required H₂ and CO₂ is imported from outside the HIC Rotterdam. The used technology configurations are modeled as 'Lego bricks' with a specific capacity and associated spatial footprint. Figure 10 shows the used Lego bricks for synthetic fuel production technologies that are used in the scenario space. Table 5 specifies the growth scenarios that correspond to the different values of external factor 6. In a similar way, the growth scenarios for the other new technologies have been defined as part of the scenario space.

External factors that govern the site locations at which these technologies are implemented

For energy infrastructure planning it is relevant which technologies are implemented at what location in a certain reference year of a scenario. Next to the uncertainty about when which technology will be implemented in the HIC Rotterdam, it is also uncertain at which geographic location (site) those technologies will be implemented.

To this end two external factors have been defined that govern the geographic integration of new technologies:

- Factor 49: technology implementation order. A certain value for this factor dictates in what order technologies are implemented at sites in a reference year.
- Factor 50: geographical filling order. A certain value for this factor dictates the way how, geographically seen, available site area in the HIC Rotterdam is filled with new conversion assets.

The combination of selected values for these external factors leads to the selection of a specific algorithm that governs the integration of new technologies across the sites where those technologies can be integrated in the reference years of a scenario (see appendix B for details).

Subsystem 2. Chlorine based chemical cluster, other industrial sites and (repowered) methane based utility production sites

External factors 10-13, 15, 16a and 51 govern the scenario generation on structural change of the sites that are part of the current chlorine based value chain. In the HIC Rotterdam a chlorine cluster is present (see figure 11). This cluster comprises a chlorine production plant and various sites that comprise chlorine demanding processes. Due to legislation chlorine may only be produced for captive or local use. This means that it is not allowed to transport chlorine over great distances. The current chlorine dependent processes are thus directly dependent on the availability of the chlorine production plant in the HIC Rotterdam. As a result, in case, in the future, this chlorine production plant would close, the production processes that use chlorine as a feedstock will have to be closed too.

Table 4: considered potential new technologies for the production of non-oil based fuel and chemical feedstock in the case study

Technology	Description	External factor governing the technology growth scenario
Green gas based naphtha production technology	Green naphtha production technology based on green methane and CO ₂ feedstock	5
Synthetic fuel production technology	Synthetic fuel production technology based on a H ₂ and CO ₂ feedstock (with varying combinations of green H ₂ production in HIC Rotterdam / H ₂ import and CO ₂ production via Direct Air Capture units in HIC Rotterdam / CO ₂ import)	6
Synthetic methanol based olefins production technology	Synthetic methanol based olefins production technology based on a H ₂ and CO ₂ feedstock (with varying combinations of green H ₂ production in HIC Rotterdam / H ₂ import and CO ₂ production via Direct Air Capture units in HIC Rotterdam / CO ₂ import)	7
Biogasification based olefins production technology	Biogasification based olefins production technology based on a biomass feedstock	8
Plastic waste gasification based olefins production technology	Plastic waste gasification based olefins production technology based on a plastic waste and H ₂ feedstock (with green H ₂ production in HIC Rotterdam or H ₂ import)	9

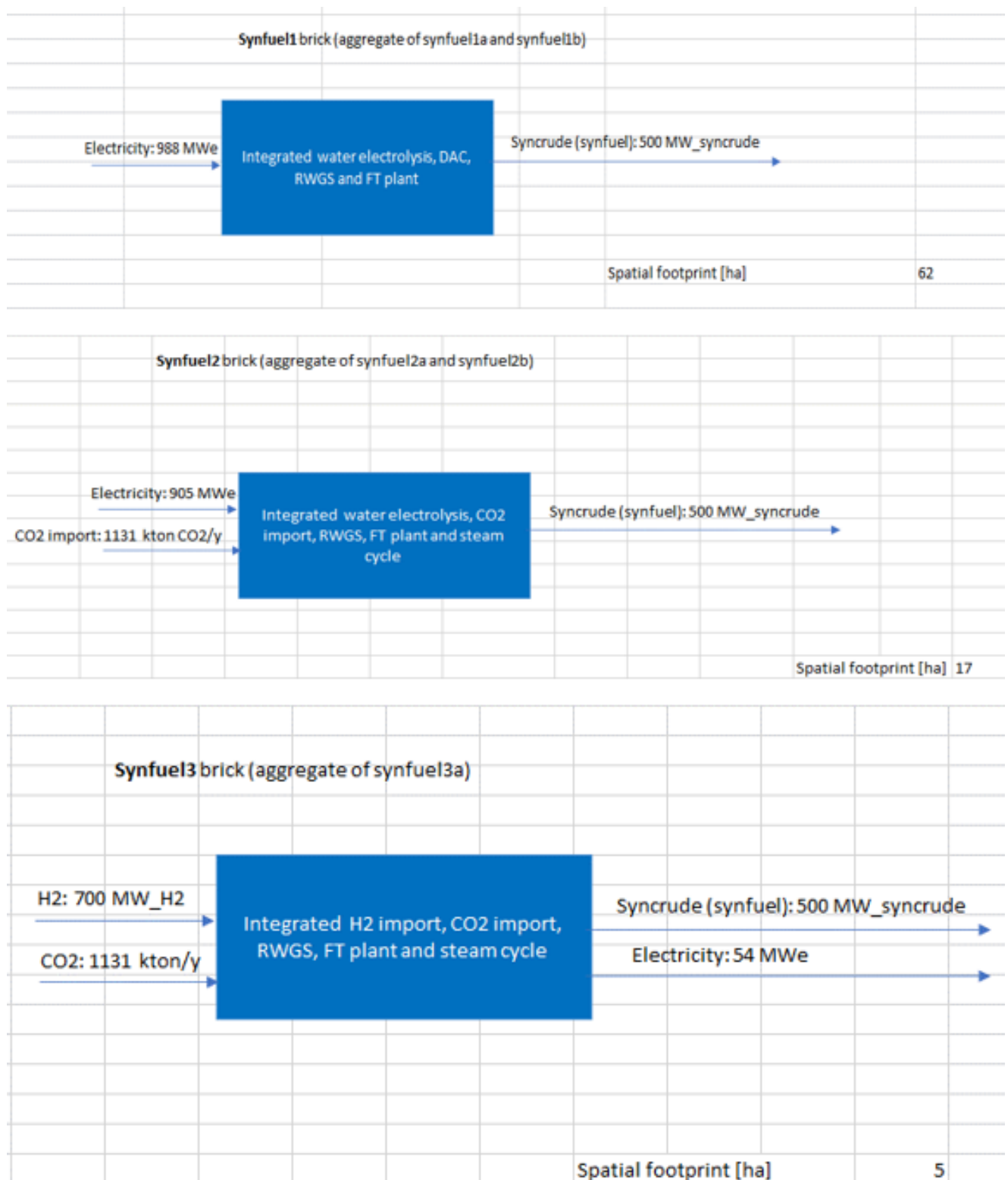


Figure 10: Technology 'Lego bricks' that are used to express the various options for synthetic fuel production technology configurations that have been taken into account in the developed scenario space

Table 5: specification of growth scenarios for synthetic fuel production capacity governed by external factor 6. '3synfuel1' means that 3 Lego bricks of technology configuration synfuel1 are installed in that specific reference year (see figure 10). 12 synfuel3 means that 12 Lego bricks of technology configuration 3 are installed. The meaning of the other texts in the cells is analogous to the explained meaning for '3synfuel1' and '12synfuel3.'

Reference year	2035	2040	2045	2050
Value external factor 6				
a. No synfuel growth scenario	-	-	-	-
b. Med. synfuel config1 growth scenario	-	3synfuel1	3synfuel1	-
c. Max synfuel config1 growth scenario	3synfuel1	4synfuel1	7synfuel1	-
d. Med synfuel config2 growth scenario	-	6synfuel2	12synfuel2	-
e. Max synfuel config2 growth scenario	6synfuel2	12synfuel2	18synfuel2	6synfuel2
f. Med synfuel config3 growth scenario	-	12synfuel3	12synfuel3	-
g. Max synfuel config3 growth	12synfuel3	12synfuel3	18synfuel3	6synfuel3

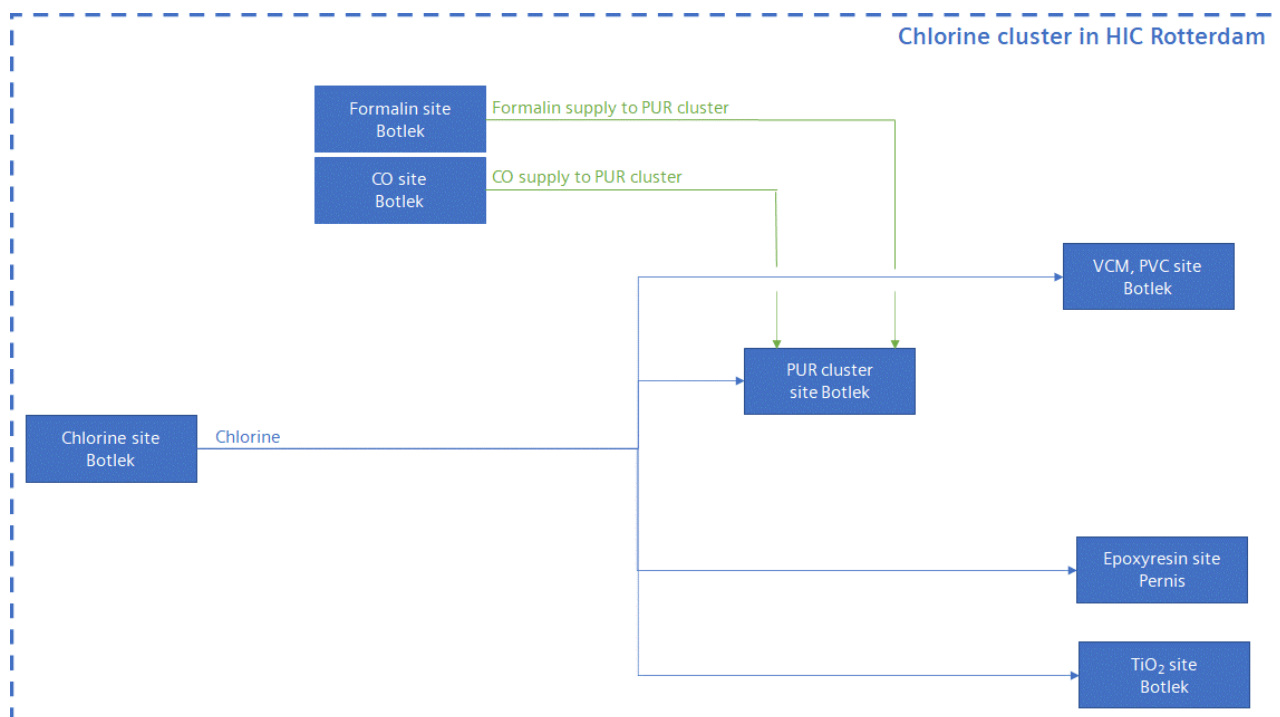


Figure 11: representation of the current chlorine cluster in the HIC Rotterdam

In the scenario space design, this site cluster interdependency has been taken into account. The potential capacity evolution of chlorine demand sites have been defined as external factor. Per external factor various values represent various capacity reduction scenarios of such a site (no capacity reduction or in a single case capacity growth is also an option). The selection of values for these factors leads in a scenario to a certain capacity evolution of these sites in the course of time. As, in a given reference year, the total chlorine consumption drops below a defined threshold value, it is assumed that the chlorine production plant cannot operate economically. As a consequence, this plant is assumed to close and the remaining chlorine demand sites will also have to close due to the chlorine dependency. In this way, the potential chain reaction between the interdependent sites of the chlorine cluster is modeled within the design of the scenario space.

At the sites of the chlorine cluster, it is assumed that H₂O electrolysis plants can be installed in the future. These plants produce H₂ for H₂-demanding processes at other sites in the HIC Rotterdam or for supply to the hinterland. External factor 15 governs the growth of these H₂O electrolysis capacity at the considered sites. Depending on the selected value for this factor, a percentage of the available free spatial area will be filled with H₂O electrolysis 'Lego bricks' (see figure 12).

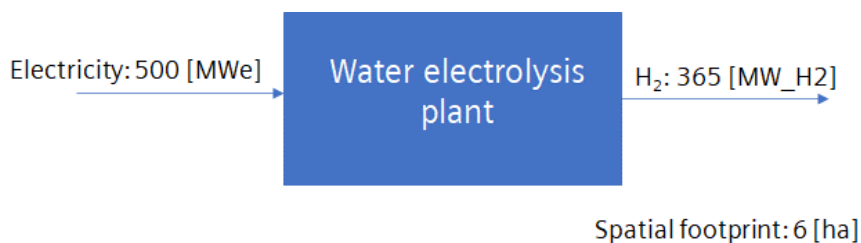


Figure 12: used 'Lego brick' for H₂O electrolysis plant integration at sites that are part of the chlorine cluster

The current processes at sites of the chlorine cluster need steam, high temperature heat and electricity for their operation. These utilities are produced with various on site and / or central conversion assets, like boilers, furnaces and cogeneration units. Nowadays, fossil methane is mainly used as energy source for these utility production assets. In the future, various different technologies can substitute the current fossil methane based utility production assets. Next to one technology replacement cycle, it can also be imagined that in the period till 2050 more than one technology replacement cycle takes place to fulfill the current functionality of the fossil methane fired conversion assets.

In the scenario space design it is assumed that technologies based on a certain energy carrier are becoming a dominant technology due to its price benefits compared to technologies based on other energy carriers. Similar to the current dominance of fossil methane fired steam boilers, it is assumed that in the future a likewise dominance of hydrogen fired boilers, E-boilers or green gas boilers could occur. Also, it can be imagined that a hybrid boiler set up could become market dominant for an intermediate period. In this set up, an E-boiler with the same steam production capacity as the current fossil methane fired boiler is added to the steam generation park. Depending on the commodity prices for fossil methane and electricity, either the fossil methane boiler or the E-boiler is operated in this set up. The last potential replacement technology for the current fossil methane fired boilers that is taken into consideration in the design of the scenario space is the H₂ hybrid boiler. This boiler technology comprises an E-boiler and a H₂-boiler. Both individual boilers possess sufficient steam production capacity to fulfill the maximum demand of the connected steam consuming assets. Similar to the hybrid boiler operation, the H₂ hybrid boiler is operated depending on the H₂ and electricity commodity prices.

In case the H₂ price is lower than the electricity price, the H₂-boiler is active. Likewise, the E-boiler is active in case the electricity price is lower than the H₂ price.

Consequently, in case in a certain reference year of a scenario the replacement of a particular steam boiler technology takes place, all installed (former) fossil methane fired steam boilers in the HIC Rotterdam will switch towards the new boiler technology.

Table 6 summarizes the considered potential boiler technologies that could replace the current fossil methane boiler technology in the HIC Rotterdam in the course of time.

Table 6: summary of considered boiler technologies that could replace the current fossil methane boiler technology

Technology	Description
Hybrid boiler	The hybrid boiler consists of a fossil methane fired boiler and an E-boiler. The E-boiler produces steam based on electricity as a feedstock and has the same steam production capacity as the fossil methane fired boiler at a site. The operation of the boiler is based on the market situation (outcome of the electricity market model). Operational modes: 1) 100% fossil methane fired boiler operation; 2) 100% E-boiler operation.
H ₂ hybrid boiler	The H ₂ hybrid boiler consists of a H ₂ -boiler and an E-boiler. The H ₂ -boiler produces steam based on H ₂ as a feedstock and has the same steam production capacity as the original fossil methane fired boiler that has been replaced. The E-boiler produces steam based on electricity as a feedstock and has the same steam production capacity as the H ₂ -boiler. The operation of the boiler is based on the market situation (outcome of the electricity market model). Operational modes: 1) 100% H ₂ -boiler operation; 2) 100% E-boiler operation.
E-boiler	The E-boiler produces steam based on electricity as a feedstock and has the same steam production capacity as the original fossil methane fired boiler at a site.
H ₂ -boiler	The H ₂ -boiler produces steam based on H ₂ as a feedstock and has the same steam production capacity as the original fossil methane fired boiler at a site.
Green gas boiler	The green gas boiler produces steam based on green gas as a feedstock and has the same steam production capacity as the original fossil methane fired boiler at a site.

Based on rules, options for boiler technology replacement paths can be generated. In table 7 the used rules for the generation of boiler technology replacement paths are shown. Application of these rules leads to 90 potential boiler technology replacement paths (see figure 13).

In a similar way, also future technology replacement options for the current fossil methane fired furnaces, power generation units and cogeneration units have been defined. Via a cross consistency impact analysis an assessment has been made on which boiler, furnace, gas fired power generation and cogeneration technologies could co-exist in the future (see table 8 for illustration of the cross consistency impact analysis).

Table 7: applied rules for the generation of boiler technology replacement paths

Technology building block	Condition for implementation in boiler technology replacement path	Possible timing of introduction of building block [reference year]
Hybrid boiler	Implementation only possible in case last technology building block is 'fossil fired boiler' (situation in 2022).	2025, 2030, 2035
H ₂ hybrid boiler	Implementation only possible in case last boiler technology change > 5 year ago AND current technology is hybrid boiler.	From 2030 onwards
E-boiler	Implementation only possible in case last boiler technology change > 5 year ago AND current technology is not 'H ₂ -boiler'.	From 2025 onwards
H ₂ -boiler	Implementation only possible in case last boiler technology change > 5 year ago AND current technology is not 'E-boiler'.	From 2025 onwards
Green gas boiler	Implementation only possible in case last boiler technology change > 5 year ago AND current technology is not 'H ₂ hybrid boiler', 'E-boiler' OR 'H ₂ -boiler'.	From 2025 onwards

Boiler technology replacement path	2025	2030	2035	2040	2045	2050
1		Hybrid boiler		H ₂ hybrid boiler		
2		Hybrid boiler			H ₂ hybrid boiler	
3		Hybrid boiler				H ₂ hybrid boiler
4		Hybrid boiler		E-boiler		
5		Hybrid boiler			E-boiler	
6		Hybrid boiler				E-boiler
7		Hybrid boiler		H ₂ -boiler		
8		Hybrid boiler			H ₂ -boiler	
9		Hybrid boiler				H ₂ -boiler
10		Hybrid boiler		Green gas boiler		
11		Hybrid boiler			Green gas boiler	
12		Hybrid boiler				Green gas boiler
13		Hybrid boiler		H ₂ hybrid boiler		E-boiler
14		Hybrid boiler		H ₂ hybrid boiler		H ₂ -boiler
15		Hybrid boiler		Green gas boiler		E-boiler
16		Hybrid boiler		Green gas boiler		H ₂ -boiler
17			Hybrid boiler		H ₂ hybrid boiler	

Figure 13: illustration of a part of the possible set of boiler technology replacement paths

Table 8: used cross consistency impact matrix that identifies which replacement technologies for fossil methane furnaces are assumed to possibly co-exist with a specific boiler technology. A cross in a cell of the table indicates that the particular furnace technology can co-exist with the particular boiler technology

Replacement option for fossil methane furnace → Replacement option for fossil methane boiler ↓	E-furnace	H ₂ -furnace	Green gas furnace	Hybrid furnace	H ₂ hybrid furnace
E-boiler	X				
H ₂ -boiler		X			
Green gas boiler			X		
Hybrid boiler				X	
H ₂ hybrid boiler					X

A utility replacement pathway in a scenario is generated by first selecting a specific boiler technology replacement path. In this pathway one or more boiler technology replacements take place in the course of the planning horizon within a scenario. Using the results from the cross consistency analysis, subsequently a furnace technology, gas fired power generation technology and cogeneration technology⁵ is selected that could co-exist with the boiler technology in a certain period of the scenario. In case of a boiler technology change in a reference year of the scenario, assessment of the cross consistency impact analysis reveals whether or not the furnace technology, gas fired power generation technology or cogeneration technology should also be replaced by another technology.

In this way, plausible scenario paths for utility production technology replacement have been drafted. From the many potential utility production paths, eight paths have been pseudo-randomly selected to represent the uncertainty about replacement paths for the current fossil methane based utility production technologies (external factor 16 a).

Selection of value a of external factor 51 will not impact the selected value for external factor 16a. However selection of value b forces external factor 16a towards an electrification pathway for utility production technologies³.

External factors 14, 15 and 16a govern the structural change evolution across the planning horizon of sites that are part of the group 'industry other'. Structural change as a result of H₂O electrolysis capacity increase is driven by external factor 15 in the same way as is described for sites that are part of the chlorine cluster. Furthermore,

⁵ Validation of scenario generation with values for external factor 16a that should lead to a switch of fossil methane fired conversion assets towards H₂ fired conversion assets led to the conclusion that this switch option was not programmed well (the methane fired conversion assets remained unaltered). Also, the functionality of external factor 51 was not implemented correctly. Recommendation for future work is to better validate the scenario generation model and improve the model according to the findings.

the potential structural change of utility production technologies that supply utilities to these sites is driven by external factors 16a and 51 in a similar way as described for the chlorine cluster. Possible scenarios for capacity reduction pathways for 'other industrial sites' are determined by external factor 14. These scenarios describe the potential evolution of the installed capacity for conversion assets at a specific site. A selected value for external factor 14 governs the reference year in which sites that are part of the group 'industry other' are closed (i.e. the year in which the capacity of the current conversion assets inhabiting these sites will be reduced to zero). Upon closure of a site, extra available spatial area is created for the potential integration of H₂O electrolysis capacity at this site.

Subsystem 3. Nuclear power plant

In the future, potential nuclear power plant capacity can be installed at the Maasvlakte area. External factor 17 encompasses various scenarios for the growth of this nuclear power plant capacity.

Subsystem 4. Onshore wind production

Various growth scenarios for onshore wind production are defined via external factor 18.

Subsystem 5. Onshore solar PV production

Factor 19 determines the growth scenario for onshore PV production that is part of a generated scenario.

Subsystem 6. Offshore wind landing capacity

Selection of a value for external factor 20 leads to a specific growth scenario for offshore wind landing capacity over the planning horizon.

Subsystem 7. Built environment

A G-gas pipeline that is running parallel to the main methane backbone (HTLH-backbone) in the HIC Rotterdam is currently used to transport G-gas towards the residential area as energy source for low temperature heating systems. Regular methane demand volumes by the residential area are supplied via a connection line (including a blending station) to the HTLH-backbone. In extreme cold weather conditions, additional methane supply via the peak shaver takes place. The methane supply to the peak shaver is extracted from the HTLH-backbone.

In case the residential area switches to a non-methane energy carrier as energy input for their heating systems, the G-gas pipeline can be reused for H₂ transport within the HIC Rotterdam. However, it is uncertain if the current G-gas users of the residential area will switch to a non-methane energy carrier in the future. In case they will switch, it is uncertain when this switch will occur. To take this uncertainty into account the external factors 24 and 25 have been defined.

Subsystem 8. Electrical charging of ships & shorepower

Various growth scenarios for electrical charging of ships and shorepower over the planning horizon are defined by external factor 26.

Subsystem 9. H₂ demand hinterland

Future H₂ demand of the hinterland (basically, the rest of the Netherlands and large parts of Northwest Europe) can be partly supplied via the HIC Rotterdam. Values for external factor 23 represent different growth scenarios for H₂ demand of the hinterland that can be supplied via the HIC Rotterdam.

Operational change

Subsystem 10. Dutch electricity market

The operation of several conversion assets that are part of the HIC Rotterdam energy system, like gas fired power plants, are driven by the electricity market. Furthermore, the electricity exchange between the HIC Rotterdam and its surroundings on an hourly basis is affected by the electricity market conditions. To account for the impact of the electricity market on the operation of the energy system of the HIC Rotterdam, an electricity market model was part of the simulation model. Since, it is uncertain how the electricity market will evolve over the planning horizon, the following external factors have been defined that lead to various scenarios of electricity market evolution during the planning horizon:

- External factor 28: 'Merit order'. In scenarios various electricity generation assets can be simultaneously present within HIC Rotterdam in a reference year of a scenario. These electricity generation assets are assumed to be part of the Dutch electricity market. However, the merit order of different electricity conversion assets in the future is unknown due to uncertain developments in commodity prices of feedstocks for these conversion assets. Therefore, the merit order has been defined as external factor. A value for this factor refers to a certain merit order of electricity generation conversion assets.
- External factor 34: 'scenario rest of NL'. The electricity market model of the Netherlands is modelled with the Energy Transition Model of Quintel. For a certain merit order, the electricity price is computed based on an assumed electricity demand and supply for the Netherlands. Due to the unknown relation between scenarios of structural change in the HIC Rotterdam and scenario developments in the rest of the Netherlands, the external factor 'scenario rest of NL' has been introduced. Values for this factor refer to different scenarios of structural change in the rest of the Netherlands affecting the electricity market dynamics.

Stakeholder dialogue

A stakeholder dialogue to gather information about future visions of the energy system evolution is part of the design process of the scenario space. Since the method is capable of exploring many scenarios, relevant scenarios for stakeholders can be incorporated into the scenario space. In the project, such a stakeholder dialogue has been executed.

The next ideas from the stakeholder dialogue have been used to enrich the preliminary design of the scenario space:

- The preliminary design of the scenario space has been adjusted to ensure that the only alternative for refinery gas and / or petcoke fired conversion assets are conversion assets that are fed by blue H₂.
- Next to the H-vision scenarios described in [21], the replacement of refinery gas / petcoke fired boilers by blue H₂ boilers is considered to be plausible. Therefore, this potential development has been incorporated in the developed scenario space.
- The potential development of central nuclear power plant capacity at Maasvlakte was added to the preliminary design of the scenario space.

Next to the ideas that have been incorporated in the developed scenario space, various other ideas about the potential evolution of the energy system could not be included in the scenario space due to scope limitations within the project. However, these ideas can be used to extend the relevant scenario space of the HIC Rotterdam in future work. These ideas have been summarized in a superstructure of the (potential) energy system of the HIC Rotterdam (see appendix E).

5.2 Investment paths (L)

The modeled energy infrastructure is composed of the following networks:

1. 380 kV-network
2. 150 kV-network
3. Medium Voltage-network (MV-network)
4. H₂-network
5. HTLH-network (methane-network)
6. ODO-network (methane-network)
7. NODO-network (methane-network)

The individual networks are composed of nodes and links. The nodes are connected to each other via the links. Nodes and links are representations of energy infrastructure elements from which the energy infrastructure is constructed.

In workshops with grid strategists of the network companies, energy infrastructure investment paths for the individual networks have been defined. An investment path comprises investments across the planning horizon for a network. To facilitate the thought process for the creation of various options for investment paths an initial set of four scenarios have been used. This small set of scenarios was useful for the imagination of investment paths that potentially could be a good starting point for a strategic direction for a robust, adaptive integrated investment path.

Table 9 highlights the type of investment paths that have been created for the individual networks. For the 380 kV- and 150 kV-networks integrated investment paths have been designed that comprise investment packages in the various reference years across the planning horizon. Likewise, various investment paths for H₂-infrastructure have been developed. For the MV-network, various investment rules served as investment path. Given a specific rule and scenario developments in a reference year, the investments in these networks will be executed during a simulation run. For the methane networks (HTLH, ODO, NODO) it was assumed that no investments were needed due to the considered general trend of declining methane transport capacity demand futures. A potential function change of the existing G-gas backbone, from the current function to transport methane towards a new function to transport H₂, was part of some of the developed investment paths.

For the finalization of the set of initial integrated investment paths, in a workshop with grid strategists from the various network companies, an assessment was made on the compatibility of the investment paths for the individual networks.

The developed set of initial investment paths is confidential. This set of initial investment paths can serve as input for the execution of step 3B of the Gridmaster method: the selection of promising candidate investment paths. Due to scope limitations this process step has not been executed during the project.

The MIEK investment path was part of the developed set of initial investment paths. This investment path, which represents the current investment path for the considered energy infrastructure for the HIC Rotterdam has been used as investment path for the examination of the added value of Gridmaster method process steps 2A, 2B, 3D, 3E and 3F. Figure 14 illustrates the structure of the MIEK investment path, which is derived from the published investment plans for the High Voltage and hydrogen networks and an assumed investment rule for capacity expansion of the MV-network [23, 24].

Table 9: structure of the composed investment paths per individual network

Network	Structure of investment path
380 kV	Realized fixed investment packages in specific reference years over the planning horizon
150 kV	Realized fixed investment packages in specific reference years over the planning horizon
MV	Rule-based investments representing a certain investment philosophy based on the rated capacity of connected customer sites to an infrastructure node and a threshold value thereof
H ₂	Realized fixed investment packages in specific reference years over the planning horizon
HTLH (methane)	No investments over the planning horizon were considered to be necessary
ODO (methane)	No investments over the planning horizon were considered to be necessary
NODO (methane)	No investments over the planning horizon were considered to be necessary

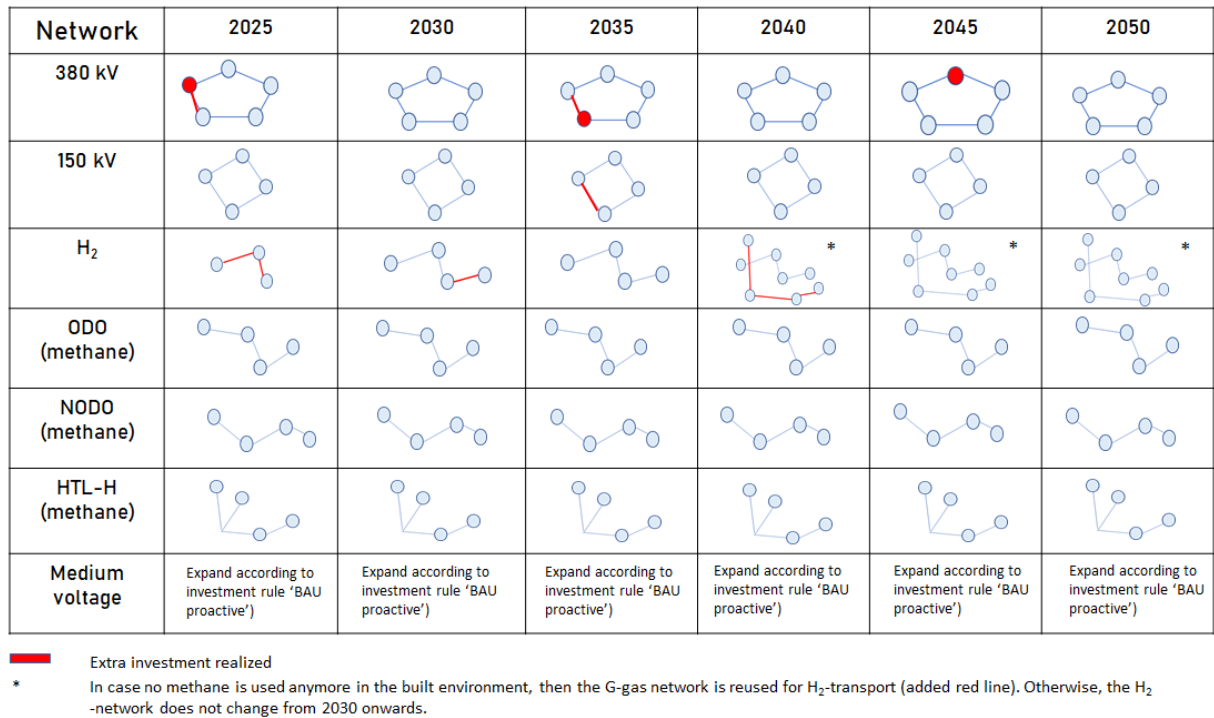


Figure 14: Schematic illustration of the structure of the MIEK investment path

5.3 Developed software simulation tool (R)

5.3.1 Overview of digital toolkit

Parts of the description of the developed software simulation tool in this section is taken from [5].

For the execution of large scale simulations a digital toolkit has been designed in the case study. Figure 15 provides a high level overview of the functional set up of this toolkit. The toolkit comprises two main tools that are interconnected. The first tool is the Exploratory Modeling Workbench. The Exploratory Modeling Workbench is an open source library implemented in Python to support the execution of a series of simulations for the exploration of the impact of deep uncertainty on the performance of a plan [25]. In the workbench the definition of simulations takes place. Hereafter, the simulations are executed by multiple runs of the simulation model. The output of the large scale simulation is subsequently analyzed with analytical tools present in the workbench.

The second tool is the multi-model simulation tool. For a specific combination of an investment path and a scenario, this tool computes the hourly overload per infrastructure element and the investment cost per year for the six reference years of the considered planning horizon. Based on this output the metrics are computed. This tool comprises the following interconnected model clusters to enable the required functionality:

1. Location-specific energy subsystem configuration model cluster
2. Energy system operations model cluster
3. Investment and networks evolution model cluster
4. Load flow model cluster

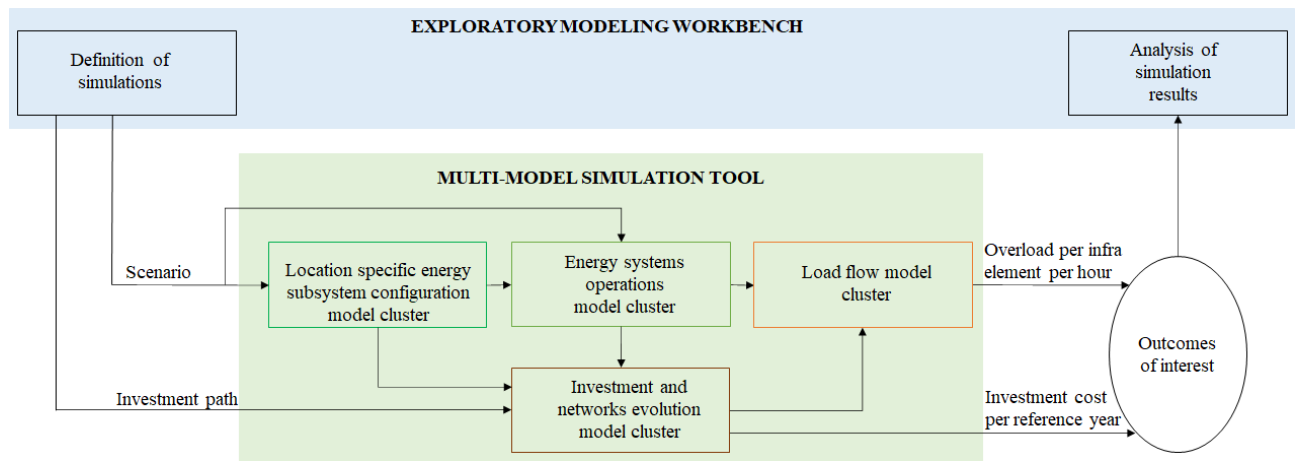


Figure 15: High level overview of the developed digital toolkit for large scale simulations to support the creation of a strategic direction for a robust, adaptive investment path for integrated energy infrastructure

5.3.2 Multi-model simulation tool

Location-specific energy subsystem configuration model cluster

This model cluster enables the modeling of site configuration changes over time. A site is a specific spatial area within the total geographic area of the considered energy system (HIC Rotterdam for the case study) at which energy conversion assets (e.g. an oil refinery, a synthetic fuel plant, or methane fired power plant) can be located. Depending on the selected scenario, the configuration of the sites in the geographic area will change during the planning horizon. In a scenario, this model provides for the six reference years an image of the installed conversion assets (capacity and type) across the sites in the considered geographical area. Furthermore, the evolution of energy exchange capacity with the surroundings for the six reference years is taken into account. The model restricts the growth of installed energy conversion assets at a site by monitoring the available spatial area for new conversion assets at a site during the evolution of a scenario. Every modeled site is connected to nodes of the integrated energy infrastructure for energy exchange.

The functionality of this model cluster can be compared with a Lego base plate at which in a scenario Lego buildings located at specific locations change in the course of time. In this analogy, the Lego base plate is representing the geographical area of the HIC Rotterdam at which (combined) energy conversion assets like synthetic kerosene factories and offshore wind parks can be located. The Lego buildings are built from Lego bricks. Here a Lego brick represents a certain energy conversion technology with a specific capacity and spatial footprint. At several locations at the border of the Lego baseplate Lego bricks represent connection points for energy exchange with the surrounding energy system. Offshore wind landing or H₂ demand from the hinterland are examples of energy exchange that can be modeled with these kind of Lego bricks.

To enable the generation of plausible scenarios of structural change the following elements have been defined:

1. Sites at which 'conversion technology Lego buildings' can be built or removed. A site has the following attributes:
 - a. A geographical location
 - b. A spatial area
 - c. A type indication that determines which conversion asset technology Lego bricks might be integrated

- d. A start configuration with Lego buildings that represent the current energy subsystem
 - e. A connection option to an energy infrastructure node. This connection can be dependent on the energy exchange capacity between the site and the energy infrastructure node.
- 2. Sites at which energy exchange with the surroundings takes place. A site has the following attributes:
 - a. A geographical location
 - b. A type indication that determines which energy carrier can be exchanged with the surroundings
 - c. A certain capacity for energy flow exchange
 - d. A start configuration with a certain energy exchange capacity that is representative for the current energy subsystem
 - e. A connection option to infrastructure nodes. This connection can be dependent on the energy exchange capacity between the site and the infrastructure node.
- 3. Conversion technology Lego bricks that represent the smallest energy subsystem that is considered in the model. A conversion technology brick has the following attributes:
 - a. A capacity
 - b. A conversion logic: certain input energy/material flows are converted with a certain efficiency to certain output energy/material flows
 - c. A spatial footprint
 - d. Operations characteristics. *E.g.* dependent on the electricity market price or given by a fixed hourly profile
- 4. Rules for building a Lego Building with Lego bricks. Which technologies can co-exist in a certain future? Which path dependencies can be assumed? For example, the implementation of CCS at oil refineries creates a path dependency. This will probably lead to a longer presence of an oil refinery operation compared to an alternative scenario in which no CCS implementation occurs. Which Lego buildings at different sites are dependent on the existence of other Lego buildings? For example, chlorine based chemical processes are dependent on the existence of the chlorine production plant. In case of a scenario event in which this chlorine production plant is assumed to close, the chlorine based chemical processes should also close. The impossibility to integrate a conversion technology Lego brick at a site that requires more spatial area than is available is implemented as a general rule which has been implemented in the project.
- 5. Slack nodes. To balance the energy system on an hourly basis slack nodes have been defined that are used to close the energy carrier balance during a simulation run at an hourly basis.

Figure 16 depicts the mapping of sites to the external factors of the scenario space. This overview has been used to program the location-specific energy subsystem configuration model cluster.

Energy system operations model cluster

This model cluster governs the operational behavior of modeled energy conversion assets at sites and the profiles of energy exchange with the surroundings on an hourly basis in a certain reference year during a scenario. One part of this model cluster is a national electricity market model that simulates electricity price profiles during a reference year of a scenario using the Energy Transition Model (ETM) of Quintel. The calculated electricity price profile serves as an input for the ESSIM-model of TNO in which on an hourly basis per site-infrastructure node energy flows are calculated using the information from the location-specific energy subsystem configuration model cluster. The electricity exchange flow between the HIC Rotterdam and its surroundings is calculated with the post processing module. Per reference year in a simulation run, for 8760 hours per year energy flows (electricity, H₂, methane) at the connections between the sites and the

infrastructure nodes are calculated. These data are used in the load flow models for the various energy carriers (part of the investment and networks evolution model cluster).

Investment and networks evolution model cluster

In this model cluster the consequence of investment paths on the evolution of the integrated energy infrastructure is modeled. Next to the time-dependent investment packages, the modeled scenario-dependent investments are changing the modeled integrated energy infrastructure in a simulated reference year. Based on rules, the connection between a site and the electricity networks is defined. For example, in case a certain threshold load value is exceeded due to a scenario development, this site is switched from the Medium Voltage substation towards a 150 kV- or 380 kV- substation. In an analogous way, a site connection to a 150 kV-node can be switched towards a 380 kV-node. The infrastructural consequence of the use of the current G-gas pipeline for H₂ transport, dependent on certain scenario developments in the built environment, is taken into account within this model cluster.

Per reference year in a simulation run, the energy infrastructure topology and associated installed capacities of energy infrastructure elements is computed in this model cluster. This serves as input for the subsequent load flow calculations conducted by the load flow model cluster.

Furthermore, this cluster computes the investment costs per reference year for a certain investment path in a certain scenario.

Load flow model cluster

This model cluster provides per reference year in a simulation run hourly calculated overloads for the energy infrastructure elements. To this end, two load flow models have been used. For the H₂- and methane networks, the MCA LIGHT loadflow module of Gasunie have been deployed. The loadflow computations for the electricity networks were conducted by a Python script created by TenneT.

Detailed functional design of the multi-model

In figure 17, a detailed schematic is shown of the designed multi-model in which the submodels are sequentially executed as indicated with their respective number. The produced data of a submodel is collected in the cloud storage. Part of this data can be used as input for a simulation with another submodel. The simulation is initiated by running submodels 1 and 2 which generate and store all input scenarios (*i.e.* energy system evolution samples) in the cloud. Subsequently, the submodels from 3 to 8 are sequentially executed per scenario. Every simulation run starts with an input scenario (*i.e.* energy system evolution sample) and an input investment path (including the energy infrastructure connection to site locations). This input data is used by the other submodels which results in the final hourly overload values for energy infrastructure elements per reference year.

		Site type													
		Electricity exchange via 380 kV link C (E3)	Electricity exchange via 380 kV link B (E2)	Electricity exchange via 380 kV link A (E1)	H2 import via shipping (H3)	Import methane east side (M1)	H2 demand hinterland (H1)	Shipping, shore power	H2 demand built environment (H2)	Methane demand built environment (M2)	Peak shaver	Off shore wind import (E5)	Onshore solar	Onshore wind	Nuclear power plant
External factor	0. CCS technology paths	x	x												
	2a. Capacity reduction Gunvor		x												
	3. Capacity reduction VPR		x												
	4. Available area Maasvlakte 2			x											
	5. Naphtha production from green gas	x	x	x											
	6. Synfuel production	x	x	x											
	7. Synthetic methanol production	x	x	x											
	8. Biogasification based olefin production	x	x	x											
	9. Plastic waste based olefin production	x	x	x											
	49. New technology implementation order	x	x	x											
	50. Geographical filling order	x	x	x											
	10. Capacity reduction PUR-MDI plant				x										
	11. Capacity reduction PVC plant				x										
	12. Capacity reduction epoxyresin plant				x										
	13. Capacity reduction TiO2 plant				x										
	14. Closure date 'other industrial sites'				x										
	15. Filling rule 0,5 GWe elektrolyzer				x	x									
	16a. Fossil utility production technology paths				x	x	x								
	51. Short-term MIEK path				x	x	x								
	17. Nuclear power plant Maasvlakte							x							
	18. Onshore wind production							x							
	19. Onshore solar PV production								x						
	20. Offshore wind landing capacity									x					
	24. Switch G-gas consumers: type and volume								x	x	x				
	25. Switch G-gas consumers: year of switching								x	x	x				
	26. Charge capacity shipping & shore power										x				
	23. H2 demand hinterland											x			
	28. Merit order order		x			x	x	x							
	34. Scenario rest NL		x			x	x	x							
	Energy carrier balancing / slack node												x	x	x

Figure 16: mapping of external factors to site types. The groups of external factors with a same color represent a particular energy subsystem that is part of the HIC Rotterdam energy system.

5.3.3 Overview of used tools

In table 10 an overview of the used software tools for design and realization of the digital toolkit is given.

5.3.4 Technical design multi-model simulation tool

For stress testing of an investment path a large number of scenarios have to be evaluated. This leads to a challenge on the scale-up of calculations for achieving acceptable lead times for the simulation phase. The technical design of the realized multi-model for the case study, that enables many simulation runs in a reasonable time frame, can be found at <https://github.com/GridMaster2022>.

5.3.5 Open source

All code used for this project can be found at <https://github.com/GridMaster2022>.

The developed scenario space and the largest part of the multi-model simulation tool is publicly available and can be used in future work. Some parts of the multi-model and data input are not publicly published due to either confidentiality reasons or due to too limited validation of the used model part. For the MCA LIGHT loadflow module of Gasunie the following disclaimers are relevant:

- Gasunie will not provide support with the application of the MCA LIGHT load flow module.
- The MCA LIGHT load flow module is suitable for research purposes. It is, however, not suitable for detailed planning calculations for the gas networks.

To recreate the fully distributed and integrated cloud solution of the multi-model, certain pre-existing knowledge of Amazon Web Services is required to fill in networking and configuration requirements to deploy the multi-model to the Cloud.

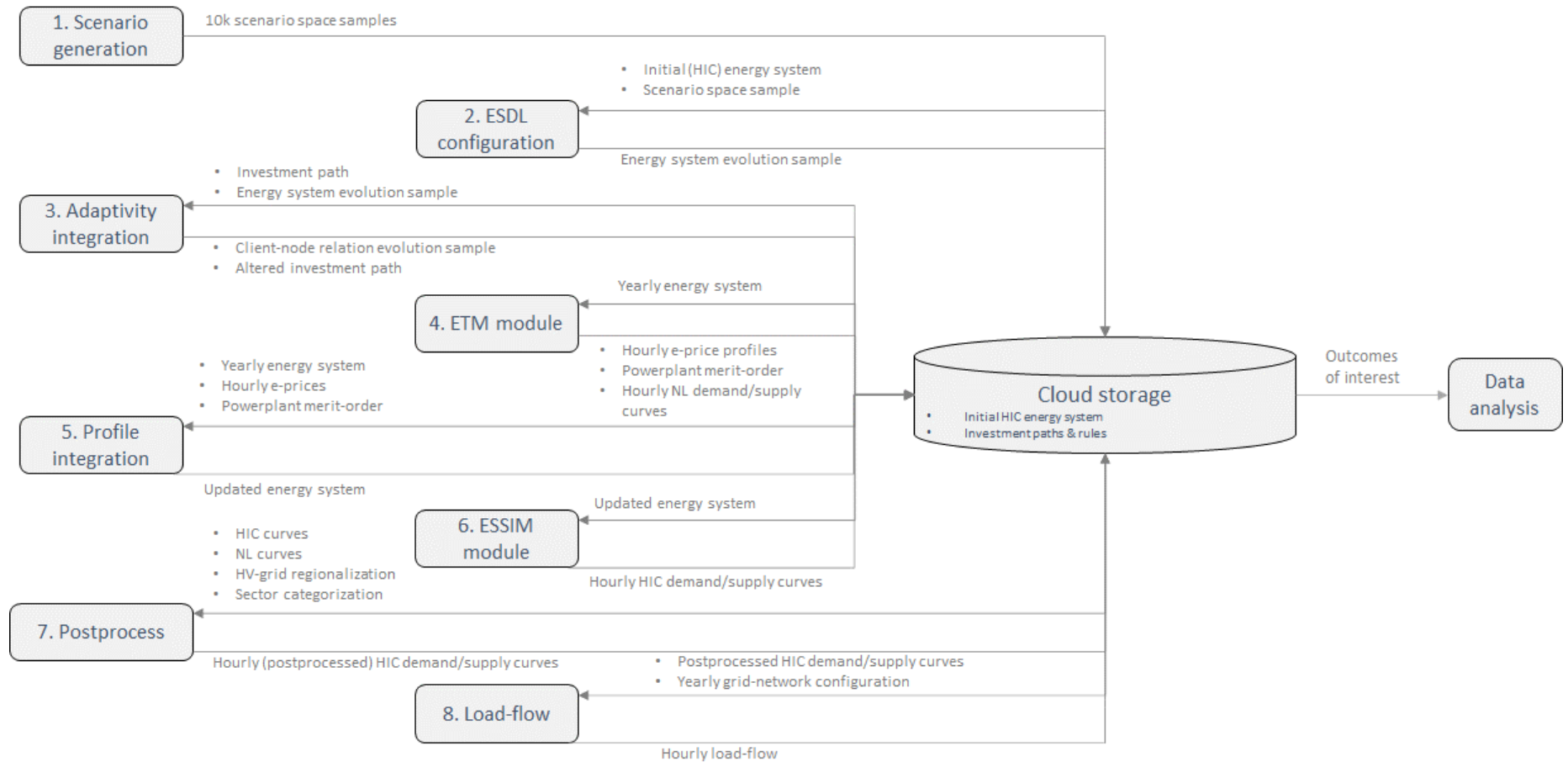


Figure 17: Detailed overview of the functional design of the developed digital toolkit

Table 10: overview of used software tools for the design and realization of the digital toolkit

Submodel	Explanatory description	Used software tool	Programmer during the project
Model of current energy system	ESDL input file containing all assets in the initial configuration of the industrial cluster.	ESSIM	Siemens
Model with rules for placing / removing technology Lego bricks at sites	Python script with 'mapping functions' that map the settings of external factors to adaptations of the ESDL input file.	Python IDE (Integrated Development Environment)	Siemens
Location-specific energy subsystem configuration model	Python script with 'mapping functions' that map the settings of external factors to adaptations of the ESDL input file.	Python IDE	Siemens TNO
Market model electricity	Advanced energy system model that is used for determination of energy prices and simulation of national energy system.	Energy Transition Model	Quintel
Model for hourly calculation of energy balances at site – infrastructure nodes	Advanced energy system simulator that is used to determine energy flows within the industrial cluster.	ESSIM	TNO
Post processing model	Python script that translates output of energy system simulations to demand/supply curves per node in an energy network.	Python IDE	TenneT
Network evolution model with rules for adaptive investments	Python script that adapts network models based on triggers for adaptive investments.	Python IDE	Siemens
Model rules for connecting sites to specific infrastructure nodes	Python script that alters the allocation of demand/supply curves to specific nodes, based on specific conditions.	Python IDE	Siemens
Station design module	Python script that alters stations in the electricity grid, based on specific conditions.	Python IDE	Siemens
Network model electricity	Representation of the electricity network	Python IDE Pandapower	TenneT

Submodel	Explanatory description	Used software tool	Programmer during the project
Network model H ₂ and methane	Representation of the H ₂ and methane networks.	MCA LIGHT	Gasunie
Loadflow model electricity	Python script that determines electricity flows within the electricity network.	Python IDE Pandapower	TenneT
Loadflow model H ₂ and methane	Software tool that determines gas flows within the H ₂ and methane network.	MCA LIGHT loadflow module	Gasunie
Metrics computation model	Python script that translates various output data to specific metrics.	Python IDE	Siemens

5.3.6 Validation of simulation tool

The various parts of the simulation tool have been validated on a sample basis before the simulation tool was used for large scale simulations. After the large scale simulation run, of which the simulation results have been used for various process steps in the case study, it appeared that the accuracy of the overload calculations is not good enough to draw quantitative conclusions about the robustness performance of the tested investment path⁶. However, the simulation results appeared good enough to show logic trends in overload patterns that can be linked to scenario events. Based on this, qualitative conclusions could be drawn.

As a next step, it is recommended, to validate and improve the whole multi-model simulation tool thoroughly, in order to enable Gridmaster analyses that rest on reliable quantitative data. Scenario generation, as an input for the model, should also be taken into account during this validation.

5.4 Metrics (M)

5.4.1 Metrics indicating impact of infrastructure on long-term energy system evolution pathways (storylines)

In process step 2C of the Gridmaster method, the objective is to determine the long-term system objective for which energy infrastructure should be developed. In a broad stakeholder dialogue, a decision is made about which directions for the long-term evolution of the energy system are socially desirable and which are not. Decision support information about the social costs and benefits of storylines for long-term energy system evolution pathways provides a vital input for this decision-making process.

An energy system evolution pathway can only be viable in case timely sufficient energy infrastructure capacity is available to support the structural change over time of conversion assets and storage assets in the considered geographic area, the altering energy exchange of the considered system with its environment and the potential change in operations of the energy system. Energy infrastructure development to support an energy system evolution pathway is part of the social costs for this pathway. To support the decision-making on which potential storylines of long-term energy system evolution are socially desirable, information about the impact on energy infrastructure is required. The impact of energy infrastructure can be seen, in the broad sense, as part of the social cost for a particular energy system evolution pathway. This social cost for energy infrastructure expansion comprises both the associated investment costs and the spatial impact.

The magnitude of overload of energy infrastructure is a measure for the social cost of energy infrastructure expansion. As a rule of thumb, the higher the overload magnitude for a specific energy network, the higher the investment costs and spatial impact of energy infrastructure expansion for mitigation of the overload. Therefore, the overload magnitude can serve as metric for the impact of energy infrastructure on long-term energy system evolution pathways.

In the project, the overload magnitude has been classified in various classes of overload magnitudes for the energy networks under consideration. This classification is a first attempt to develop a metric on overload magnitude that can provide information on the impact of energy infrastructure in storylines of energy system evolution pathways.

⁶ Details on encountered problems with computed overload values for the HTLH-, 380 kV- and 150 kV-networks have been reported separately during the project.

Overload computation for infrastructure elements and networks

In order to classify the overload magnitude of an energy network, it is necessary to define the way how the overload magnitude per network is determined. In the project it has been decided to choose different avenues for the measurement of overloads in the electricity networks (380 kV, 150 kV, MV) and gas networks (H₂, methane (HTLH, ODO, NODO)).

Overload computation in electricity networks

The basis for the computation of the overload for an electricity network, is the calculated overload duration for individual infrastructure elements that belong to the considered electricity network. The obtained hourly values of overloads of infrastructure elements during a reference year of simulation, serve as data input for the calculation of the overload duration of an electricity infrastructure element. The overload duration of an electricity network element is calculated as follows:

$$\text{Overload duration electricity infra element} = \frac{\text{overload magnitude of median of set of overload values} *}{\text{number of overload values}} \quad (1),$$

where overload values refer to the simulated hours in which the load of the infrastructure element is higher than the grid secure capacity of the infrastructure element. The unit for the computed overload duration is MWh.

An electricity network is composed of infrastructure elements that are mutually connected via a certain network topology. For the calculation of the overload duration of an electricity network, the topology of this network matters. Two extreme network topologies can be distinguished:

1. Network type A: every overload situation of an infrastructure element is independent of the overload situation of other infrastructure elements in the network.
2. Network type B: a network with equal capacities of the infrastructure elements and injection to or extraction from the electricity network at the physical ends of the network: an overload situation leads to the simultaneous overloading of all infrastructure elements.

Ad 1) for this network type, the not transported amount of electricity⁷ on a yearly basis can be calculated as follows:

$$\text{Overload network_typeA} \left[\frac{\text{TWh}}{\text{y}} \right] = \frac{\text{sum of overload duration of electricity infra elements}}{1000,000} \quad (2)$$

Ad 2) for this network type, the not transported amount of electricity on a yearly basis can be calculated as follows:

$$\text{Overload network_typeB} \left[\frac{\text{TWh}}{\text{y}} \right] = \frac{\text{sum of overload duration of electricity infra elements}}{1000,000 * \text{number of electricity infra elements}} \quad (3)$$

The MV-network is modelled as a network type A. Therefore, the overload for this network is calculated by means of equation 2. The 380 kV- and 150 kV-networks have ring structures and can be seen as networks with topologies between the described extreme network topologies. Therefore, equation 2 should be multiplied

⁷ In the project the not transported amount of electricity was used as an indicator for the magnitude of an overload situation in case no remedial action is taken. In reality, remedial action is taken to mitigate transport congestions as much as possible.

with a 'topology factor' to estimate the overload value for these networks (see equation 4). This topology factor should, theoretically, lay between 1 and 1/(number of infrastructure elements).

$$\text{Overload network 380 kV or 150 kV} \left[\frac{\text{TWh}}{\text{y}} \right] = \text{topology factor} * \frac{\text{sum of overload duration of electricity infra elements}}{1000,000} \quad (4)$$

For the 380 kV- and 150 kV-network an analysis has been conducted of the obtained overload patterns in various scenarios. The topology factor for the networks was determined using assumptions on which scenarios should not lead to unacceptable overload situations and the highest value for not transported electricity via the 380 kV- or 150 kV-network for which no investment is required (that overload situation can be dealt with by congestion management measures)⁸.

Overload computation in gas networks

The basis for the computation of the overload for a gas network, differs from the basis that is used for the overload calculation for an electricity network (described above). Instead of the overload duration of an infrastructure element, for gas infrastructure elements a length-weighted overload capacity is used as basis. This is computed as follows:

$$\text{Length – weighted overload capacity gas infra element} [MW * km] = \frac{\text{overload magnitude of median of set of overload values} * \text{number of positive overload values} * \text{length of gas infra element}}{8760} \quad (5),$$

Where 8760 refers to the number of hours in a year and the length of an infra element is expressed in km. The length-weighted capacity for gas infrastructure elements can be summed to obtain the length-weighted overload capacity of the corresponding gas network:

$$\text{Length – weighted overload capacity gas network} [GW * km] = \frac{\text{Sum of length-weighted overload capacity of gas infra elements}}{1000} \quad (6)$$

In contrast to the computation for the electricity network, no 'topology factor' has to be applied for the calculation of the length-weighted overload capacity for a gas network from values for the length-weighted overload capacity of the gas infrastructure elements the network is composed of.

Overload classes for individual networks

For the 380 kV-, 150 kV- and MV-network, the overload classes are expressed in TWh/y. A value for a computed overload for one of these networks in a reference year represents the quantity of electricity that can not be transported in that year. For relatively small overloads no expansion investment is necessary since these overloads can be mitigated with congestion management measures. A specific maximum overload value for the 380 kV-network is assumed to be mitigated by congestion management measures. Overloads higher than this threshold value require expansion investments. For the classification of overload values for the 380 kV-network, overload class 1 comprises overload values that do not require investments in the 380 kV-network. Via data analysis (150 kV) and a rule of thumb approach (MV) scaling factors have been determined in order to derive the range for the overload class 1 for the 150 kV- and MV-network, based on the defined overload class for the 380 kV-network.

For overloads that do not belong to overload class 1, investments in the network should be executed. Analysis of the overload patterns over time that arise during the exploration of overload development of the current

⁸ This analysis has been separately reported within the project

investment path in many scenarios, led to the definition of other overload classes for the 380 kV-network. In this analysis, the maximum overload value in a reference year was used as maximum value of an overload class. Application of the determined scaling factors, led to the corresponding overload classes for the 150 kV- and MV-network.

In contrast to the overload computation for the electricity networks, the overload computation for the H₂- and methane networks is expressed in GW*km. Analyses for the H₂-network were leading for the determination of overload classes for the H₂- and methane networks. It was assumed that the overload classes for the methane networks correspond to the determined overload classes for the H₂-network. Overload class 1 corresponds to overload magnitudes that do not require expansion investments. It was assumed that the maximum calculated overload value for the H₂-network in reference year 2025, in the dataset arising from the exploration of overload development of the current investment path in many scenarios, will not require expansion investments. This value was taken as upper bound for overload class 1 for the H₂- and methane networks. The other overload classes for the H₂-network have been determined in the same way as for the 380 kV-network.

Table 11 shows the developed overload classes for the networks that were considered in the case study. Due to confidentiality reasons, these values are expressed in percentage of the maximum overload value that was calculated for a network.

Table 11: overload classes for the considered networks

	Overload class					
Network	Class 1	Class 2	Class 3	Class 4	Class 5	Class 6
380 kV [% of max. overload]	0-1	1-3	3-9	9-15	15-60	>60
150 kV [% of max. overload]	0-3	3-10	10-30	30-53	>53	NA
MV [% of max. overload]	0-7	7-23	23-66	>66	NA	NA
H ₂ [% of max. overload]	0-0.081	0.081-1	1-11	11-21	21-38	>38
Methane [% of max. overload]	0-0.081	0.081-1	1-11	11-21	21-38	>38

These developed overload classes should be seen as a first version of using overload classes as a metric for the impact of energy infrastructure. It is recommended to further develop the overload classification method as metric to express the social cost of infrastructure expansion needs at various storylines of the energy system evolution. This overload classification method should be co-developed with the development of the method for the computation of overload values for energy networks.

5.4.2 Performance metrics investment path

For the development of a strategic direction for a robust, adaptive investment path for integrated energy infrastructure, it is necessary to determine metrics that indicate the performance of an investment path in many

scenarios. This paragraph describes which metrics have been defined for application in the case study. The developed metrics play a role in part 3 of the Gridmaster method: the development of a strategic direction for a robust, adaptive investment path.

Performance attributes of investment path

In discussions within the project team, the following attributes of an investment path emerged as relevant when determining its performance in a deep uncertain future:

1. Performance on capacity: this indicates the ability of an investment path to facilitate a broad range of scenarios, *i.e.* to provide timely sufficient transport capacity during the planning horizon.
2. Performance on investment costs: this indicates the costs associated with the adjustment of the energy infrastructure during the planning horizon.
3. Performance on feasibility: this specifies the feasibility of the investment path. Aspects of feasibility include the expectation about the availability of sufficient manpower and components for the realization of the investment path.
4. Performance on spatial integration: this indicates the spatial impact on the environment. The spatial footprint of the investment path and the location thereof are relevant elements of this spatial impact.
5. Performance on utilization of realized transport capacity: this indicates the potential of an investment path to be optimized from a cost perspective by moving investments backwards. The lower the utilization of the realized transport capacity, the higher the probability that the investment path can still be optimized from a cost perspective.

Due to scope limitations within the project, it has been decided to only use the performance on capacity and the performance on investment costs in the case study for the evaluation of the performance of a candidate investment path. In the executed case study, the MIEK investment path was chosen as candidate investment path.

Metrics for performance measurement of an investment path across a broad range of scenarios

In figure 18 an overview is given of the robustness metrics that have been used in the case study for measuring the robustness performance of the candidate investment path.

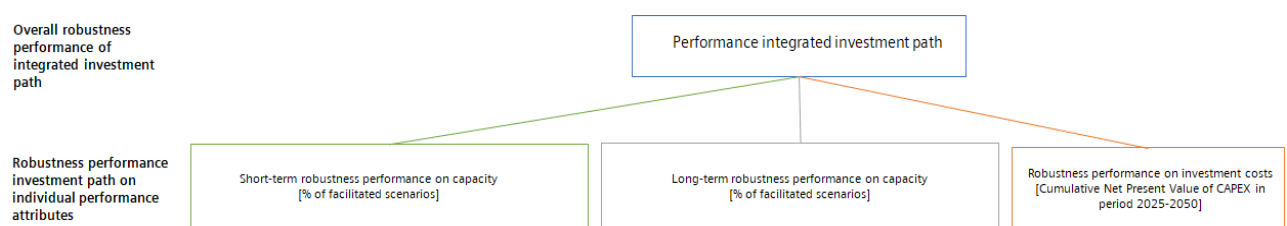


Figure 18: overview of the definition of the robustness performance used for the evaluation of the performance of a candidate investment path in the case study (the MIEK investment path was used as the candidate investment path in the case study)

The performance of an investment path is a trade-off between its performance on the following aspects:

1. Short-term robustness on capacity
2. Long-term robustness on capacity
3. Robustness on investment costs

Short-term robustness on capacity

The short-term robustness performance on capacity expresses the ability of an investment path to successfully facilitate scenarios in the short run. The timeframe that is considered as short-term is the period in which it is not possible to significantly change the transport capacity in energy networks apart from the short-term investments that are part of the candidate investment path. This timeframe varies between networks. This is due to the different lead times for the realization of planned investments for the various networks. For example, a normal lead time for a huge capacity expansion project for 380 kV-network can last ca. 10 years, while the lead time for a capacity expansion project for the MV-network is normally less than 5 years. The short-term robustness performance on capacity per network is calculated as the percentage of scenarios that meet the short-term conditions for providing sufficient transport capacity. In this definition we assume that every scenario is equally probable. The first condition is met when the overload of the network falls in overload class 1 in the reference year that corresponds with the short-term timeframe. The second condition is met when the overload of the network is lower than the maximum value within a particular threshold overload class in the reference year after the reference year that corresponds with the short-term timeframe. Condition 2 relates to a supposed maximum possible ramp up rate of investments in a 5-year period. In case a steep increase of transport capacity is required within five years, then the required additional investments to sufficiently increase the transport capacity in this short timeframe can be supposed to be infeasible.

Table 12 shows the conditions that have been defined per network that should be fulfilled in order to indicate a successful facilitation of a scenario in the short run. For the computation whether or not the conditions are met for a scenario, the defined overload classes are used (see table 11).

In case both conditions are met, then a scenario can be facilitated by the investment path in the short run. In case one of the conditions are not met, then a scenario cannot be facilitated by the investment path in the short run.

The short-term performance on capacity can be calculated per network. Additionally, the short-term performance on capacity can be calculated for the integrated investment path. In this case, a scenario can be successfully facilitated in the short run in case all energy networks can facilitate this scenario in the short run.

The short-term capacity performance of an investment path can be increased by planning additional investments that impact the transport capacity in the short run.

Long-term robustness on capacity

The long-term robustness performance on capacity expresses the ability of an investment path to successfully facilitate scenarios in the long run. The better the performance of an investment path on this aspect, the more scenarios can be facilitated in the long run. In other words, the risk of the inability to facilitate scenario developments in the long run will become lower with better performance on this aspect.

Table 12: conditions that should be both met for a successful facilitation of a scenario on the short-term.

Network	Condition 1		Condition 2	
	Reference year	Not exceeding overload class	Reference year	Not exceeding overload class
380 kV	2035	1	2040	3
150 kV	2030	1	2035	3
Medium Voltage	2025	1	2030	3
H2	2030	1	2035	4
HTLH	2030	1	2035	4
ODO	2030	1	2035	4
NODO	2030	1	2035	4

The long-term robustness on capacity is expressed as the percentage of scenarios that can be facilitated in 2050. Overload class 1 represents overload impacts on the infrastructure that do not lead to unacceptable congestion. Higher overload classes, represent overload impacts that require expansion investments in the energy infrastructure to prevent unacceptable congestions. Consequently, the long-term robustness on capacity for a (set of) network(s) is calculated as follows:

$$\text{Long-term robustness on capacity}_{\text{network}} = \% \text{ scenarios in overload class } 1_{\text{network}} \text{ in 2050} \quad (7)$$

Robustness on investment costs

The MIEK investment path that is used in the case study, comprises both fixed investments and adaptive investments over the planning period. Fixed investments are investments that are realized in a reference year independent of the scenario. Adaptive investments, on the other hand, are realized dependent on scenario developments over the planning horizon.

The cumulative net present value calculation for an investment path in a single scenario is calculated as follows:

$$\text{Cumulative net present value}_{\text{single scenario}} = \text{Sum of net present values of investment costs across the reference years in a scenario} \quad (8),$$

in which the cumulative net present value of investments in reference year x is calculated via:

$$\text{Cumulative net present value of investment cost}_{\text{year } x} = \frac{\text{cumulative investment cost in year } x}{(1+WACC)^{(x-2022)}} \quad (9),$$

where WACC stands for the weight average cost of capital. A WACC of 3% is assumed⁹ in the calculations within the case study.

Since a part of the MIEK investment path contains adaptive investments, the investment costs of an investment path differ per scenario. Therefore, the performance of an investment path is expressed by means of a robustness calculation on the calculated values for the performance indicator on investment costs across the considered scenarios. In the case study it was decided to use the mean value of computed performance

⁹ A WACC of 3% is in line with the method decision of the ACM (regulatory body in the Netherlands) for a reasonable return on investment for the period 2017 - 2021

indicators for the individual networks and the energy infrastructure as robustness metric for the investment cost performance of the MIEK investment path.

5.4.3 Metrics for overload magnitude of energy infrastructure elements

In case the short-term capacity performance is judged as insufficient, robust investments should be added to the investment path. These investments are targeted to achieve a better short-term capacity performance. To define options for robust investments, it is necessary to get insight into the overload patterns on an infrastructure element level. This enables a better understanding about the contribution of individual infrastructure elements to the observed overload situations of the network. In other words, this leads to guidance information about which investments should be added to the investment path for an increase of its short-term capacity performance.

Some directions of future evolutions of the energy system will in the long run not lead to an increased transport capacity demand. On the contrary, other future directions of energy system evolution could, in the long run, lead to a rise in transport capacity demand. For these futures, adaptive investments should be incorporated in the investment path to timely deal with the corresponding rising transport capacity demand. An adaptive investment is an investment that is linked to a specific direction of the evolution of the energy system. In case this direction is likely to evolve, the corresponding adaptive investment should be initiated to timely increase the available transport capacity that is required for the facilitation of this direction. For the design of adequate adaptive investments, it is necessary to understand the overload evolution of infrastructure elements in the directions of energy system evolution that require those investments for infrastructure elements.

To enable the definition of options for robust and adaptive investments, overload classes, derived from the defined overload classes for the networks the infrastructure elements belong to, should be defined. These overload classes indicate the order of magnitude of overloading of infrastructure elements. This metric can be used to understand the overload patterns over time, on an infrastructure element level, across many scenarios or a subset thereof.

Table 13 highlights the overload classes for the infrastructure elements per network that have been applied in the case study.

Table 13: overload classes for infrastructure elements for the considered energy networks in the case study

Network to which infrastructure elements belongs to	Applied rules to calculate the overload classes for infrastructure elements
380 kV or 150 kV	$\text{Range of overload class}_{\text{infrastructure element}} = \frac{\text{range of overload class}_{\text{network}} * \text{topology factor}}{(\text{number of infrastructure elements the network is composed of})} \quad (10)$
MV, H ₂ , methane (HTLH, ODO, NODO)	$\text{Range of overload class}_{\text{infrastructure element}} = \frac{\text{range of overload class}_{\text{network}}}{(\text{number of infrastructure elements the network is composed of})} \quad (11)$

6. Creation of storyline-overload relations

6.1 Introduction

A storyline is a set of scenarios that represents a certain subspace of the scenario space that leads to a specific distinctive overload pattern. These storylines are constructed from the external factors (dimensions of the scenario space) that significantly impact the evolution of overload of energy networks over time. In fact, the storylines describe the main scenario directions, relevant for energy infrastructure planning, the energy system can evolve to. By understanding what these storylines are, the planner of energy infrastructure is enabled to differentiate between primary and secondary things that impact the future transport capacity demand. Instead of all dimensions of the scenario space, a subset of these dimensions encompasses the primary development directions of the energy system that mainly determine the future evolution of the demanded transport capacity. Insight into the relation between scenario storylines and overload patterns over time enable grid operators to provide information about the impact of energy infrastructure on long-term energy system evolution pathways. This information supports decision-making on socially desirable storylines for the long-term evolution of the energy system.

In the case study, it was decided to focus on the 380 kV- and H₂-networks for the creation of storyline-overload relations over time, given the current investment path¹⁰. The objective was to examine whether it was possible to develop storyline-overload relations over time that could practically inform a decision-making process on socially desirable storylines for long-term energy system evolution pathways for HIC Rotterdam with information about the impact of energy infrastructure. In this section, the approach for the creation of the storyline-overload relations and the achieved results are described.

6.2 Exploration of overload development for 380 kV- and H₂-networks in many scenarios for current investment path (step 2A of Gridmaster method)

Execution of process step 2A of the Gridmaster method is the first step towards insight into the impact of energy infrastructure on long-term energy system evolution pathways. In this step, overload development over time for the energy infrastructure is explored in many scenarios for the current investment path.

6.2.1 Simulation procedure

For this exploration, a uniform sample of 10,001 scenarios from the scenario space was generated using Latin hypercube sampling across the external factors. Ten scenarios, constructed by experts, were added to this sample¹¹. This set of scenarios served as a representation of the deep uncertainty of energy system evolution pathways over time. Subsequently, 10,011 simulations were conducted, using the developed simulation tool, in which the impact of energy infrastructure was explored in these scenarios using the current investment path.

¹⁰ The MIEK investment path was as current investment path in the case study

¹¹ In the project no distinction has been made between the ten scenarios constructed by experts and the 10,001 scenarios obtained via uniform sampling in the subsequent analyses. In future work, it might be interesting to examine the added value of additional scenarios constructed by experts on top of the scenario set obtained by uniform sampling.

For 9,980 of the 10,011 scenarios overload values for all reference years for all considered energy networks (380 kV, 150 kV, MV, H₂, HTLH, ODO, NODO) were generated. 99.7% of the simulated scenarios led to a complete set of generated overload results. In 31 scenarios at least one overload value was not generated correctly. Therefore, simulation results for these scenarios were not used in subsequent analyses. The lead time for simulation of the 10,011 scenarios was ca. 1.5 weeks.

6.2.2 Results

Figures 19 and 20 show the overload patterns for the 380 kV- and H₂-networks in the 9,980 scenarios, respectively. In these figures, 9,980 lines are plotted that show the evolution of overload magnitudes for the considered networks for the explored scenarios.

These figures show different patterns of overload during the planning horizon, depending on the scenario that is explored. Some scenarios lead to huge overloads in the course of time while other scenarios result in low overload values during the course of time. It is clear that for both the 380 kV- and the H₂-network overload values arise in certain scenarios that exceed overload class 1. This means, that facilitation of these scenarios requires additional investments on top of the investments that are part of the current investment path. This observation leads to the conclusion that it is worthwhile to examine which storylines of energy system evolution could be distinguished that have the most impact on the development of transport capacity demand over time. This conducted examination is described in the next paragraph.

1.1.3 Timeseries Graph 380KV

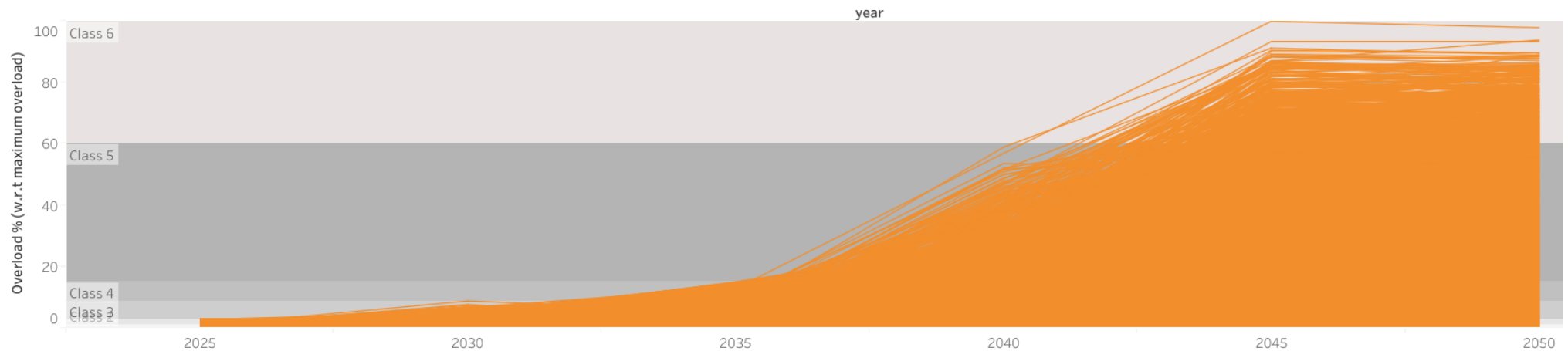


Figure 19: overload patterns over time for the 380 kV-network in 9,980 scenarios for the current investment path. As mentioned in paragraph 5.3.6, the absolute values for the calculated overloads are not accurate enough for drawing quantitative conclusions. The obtained overload patterns can be used for examination of storyline-overload relations in a qualitative way. Further validation and improvement of the multi-model tool and the developed scenario space is required for enabling 'quantitative' decision-making.

1.1.4 Timeseries Overload Curve Gas Graph H2

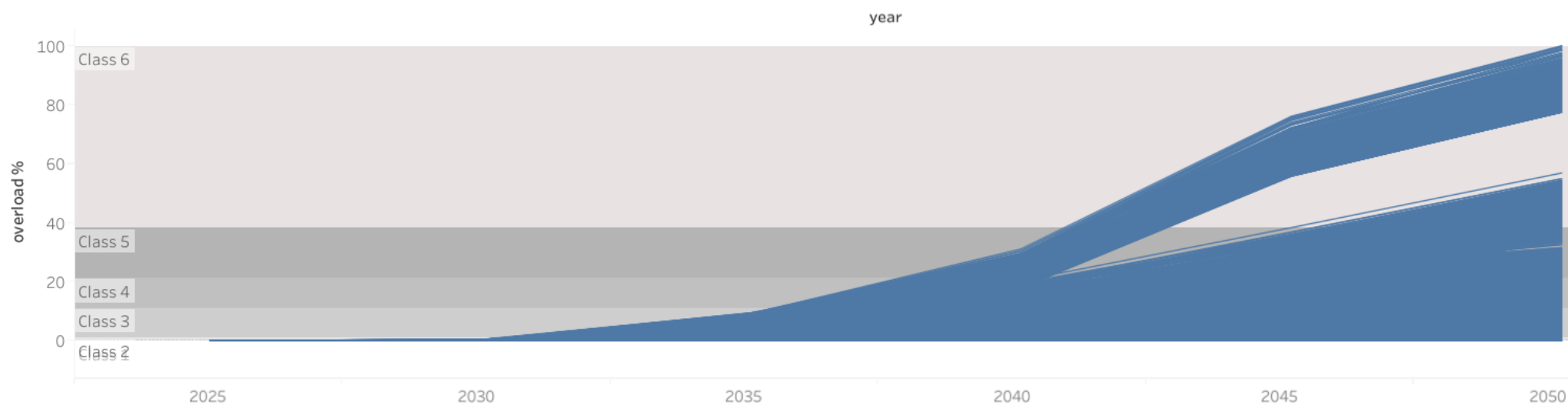


Figure 20: overload patterns over time for the H₂-network in 9,980 scenarios for the current investment path. As mentioned in paragraph 5.3.6, the absolute values for the calculated overloads are not accurate enough for drawing quantitative conclusions. The obtained overload patterns can be used for examination of storyline-overload relations in a qualitative way. Further validation and improvement of the multi-model tool and the developed scenario space is required for enabling 'quantitative' decision-making.

6.3 Examination of dominant scenario developments for energy infrastructure planning over time (step 2B of Gridmaster method)

6.3.1 Analysis method

The following three steps have been executed for the creation of storyline-overload relations:

- 1 Classification of overload time series
- 2 Patient Rule Induction Method (PRIM)-analysis
- 3 Synthesis of storylines

Classification of overload time series

For PRIM-analysis it is necessary to split a dataset into two separate groups, *i.e.*, the group for which drivers from the scenario space are looked for, and the rest of the dataset. To this end, classification of the overload time series in different groups has been executed in the case study. Two methods have been applied:

1. Classification per overload class per reference year
2. Classification per time series cluster obtained by application of a time series clustering algorithm

Classification per overload class per reference year

By using the defined overload classes (see paragraph 5.4.1), it was possible to isolate time series that fall into a specific overload class in a particular reference year from the rest of the time series. Here, a time series comprises the sequence of overload values per reference year for a certain scenario for a particular network. In this way, per reference year, scenarios leading to overload values that fall into a certain overload class were separated from the rest of the scenarios. This enabled the conduction of PRIM-analyses that were aimed at identification of drivers from the scenario space that lead to a certain overload magnitude in a reference year for a specific energy network.

Classification per time series cluster

Also, classification of overload time series has been applied as a method to differentiate between groups of data. By application of Complexity-Invariant Distance time series clustering, groups of time series were created. The applied time series clustering method was based on reference [26].

Patient Rule Induction Method (PRIM)-analysis

PRIM is a factor mapping approach aiming to identify sensitive ranges of uncertain factors that are likely to cause a particular outcome [10]. In other words, PRIM is a systematic manner to find which combinations of the model input parameters lead to specific results of interest, *i.e.* cases where output variables are in specified areas of the results space [27]. In the case study, the overload magnitude in a network for a certain reference year or the overload pattern over time for a network was used as the output variable of concern. The aim of PRIM analyses was to find drivers in the scenario space that are good predictors for the examined output of

interests, *i.e.* a specific overload range in a reference year or a specific dynamic overload pattern over the planning horizon.

For a PRIM analysis two inputs are required. The first input is the classification of output data into two groups:

- 1 A group with data comprising the outputs of interests. This data group comprises data for which the analyst is looking for drivers from the scenario space. Scenarios that lead to 380 kV overloads in overload class 2 in reference year 2040, is an example of a data set with outputs of interests. In this example, the analyst is interested in understanding which values for external factors (or combined values for different external factors) are predictors for an overload magnitude of class 2 for the 380 kV-network in 2040.
- 2 A group with the rest of the data.

The second input is the scenario input space or a part thereof. In the case study, the scenario space comprised 29 categorical external factors with various numbers of values (see paragraph 5.1.4).

A PRIM-analysis yields 'PRIM-boxes' of the model input space. A PRIM-box is a very concise representation, for typically only a limited set of dimensions of the model input space is restricted [28]. Per external factor (a dimension of the box) the range of values are reported that are part of the indicated scenario input space that is a predictor for the outputs of interests.

The quality of a PRIM-box is measured with three criteria: coverage, density, and interpretability. Coverage, is the fraction of data in the dataset 'outputs of interests' contained within the PRIM-box. Density is the fraction of cases within the PRIM-box that are part of the dataset 'outputs of interests'. Interpretability, the ease with which the PRIM-box can be communicated to and understood by policy makers, is typically measured heuristically as the number of restrictions used to define the PRIM-box. Improving any one of these three measures often negatively impacts one or both of the others [29].

The method to find multiple PRIM-boxes, as suggested in [27] has been applied. As an outcome of a PRIM-analysis, multiple potential boxes are highlighted with different quality characteristics (coverage, density and dimensions of the box (measure for interpretability)). As a guideline, boxes were selected with a density ≥ 0.8 [30]. P-values for a found dimension / external factor should be lower than 0.05. In case no PRIM-boxes were found with a density ≥ 0.8 the analysis was stopped.

Software functionality to conduct PRIM-analyses, available in the EMA-workbench, has been used for the execution of the PRIM-analyses.

Example of PRIM-analysis

Below, an example is shown of one of the conducted PRIM-analysis for illustrative purposes.

In the example, the following question was the basis for the PRIM-analysis: which combinations of values in the scenario space are predictors for overload values for the H₂-network of overload class 3 magnitude in 2040?

Figures 21 and 22 show the obtained results from the PRIM-analysis. From the PRIM-box options that have been found during the first analysis round 'box number 3' was selected. This box fulfills the criterion of a density ≥ 0.8 and has a coverage of 0.84. The box describes the following scenario area: a H₂ hinterland demand between 7 – 20 GW_H₂ combined with a H₂ import that is smaller than 17 GW_H₂ in 2040. The obtained result from the first PRIM-box means that 84% of the scenarios that lead to a H₂ overload magnitude in overload class 3 in 2040 is a result of a combination of a H₂-hinterland demand between 7 – 20 GW_H₂ and a H₂ import lower than 17 GW_H₂ in 2040. 20% of the scenarios that comprise the described scenario area in the first PRIM-box does not lead to a H₂-overload in class 3 in 2040.

After selection of the first PRIM-box, potential PRIM-boxes were found in the second analysis round. 'Box 15' was selected from the presented options. This box also met the density criterion and had a coverage of 0.11. This box describes the following scenario area: a H₂ hinterland demand between 5 – 7 GW_H₂ combined with a H₂ import between 4 – 20 GW_H₂ in 2040. The obtained result from the second PRIM-box means that 11% of the scenarios that lead to a H₂ overload magnitude in overload class 3 in 2040 is a result of a combination of a H₂-hinterland demand between 5 – 7 GW_H₂ and a H₂ import between 4- 20 GW_H₂ in 2040. 20% of the scenarios that comprise the described scenario area in the second PRIM-box does not lead to a H₂-overload class 3 in 2040.

Please note that the used overload data for the PRIM-analyses for the 380 kV-network were not calculated correctly from the overload values of the corresponding infrastructure elements. The 'topology factor', as explained in paragraph 5.4.1 was not applied in the computation of overload values for the network. Furthermore, it appeared that data handling has led to an incomplete dataset. Although the quality of analysis was affected by this, the PRIM analyses still revealed drivers for certain overload situations over time that seem plausible in a qualitative sense. From the PRIM-analysis results, information about the dimensions of the input parameter space, that drive overload conditions for the 380 kV-network could be revealed. This information has been used as input for the storyline synthesis.

	coverage	density	id	mass	mean	res_dim
0	1.000000	0.446908	0	1.000000	0.446908	0
1	1.000000	0.596136	1	0.749675	0.596136	1
2	0.873044	0.781044	2	0.499550	0.781044	1
3	0.842423	0.801915	3	0.469484	0.801915	2
4	0.819624	0.822013	4	0.445610	0.822013	2
5	0.791238	0.835891	5	0.423035	0.835891	2
6	0.749441	0.853398	6	0.392468	0.853398	2
7	0.704962	0.879532	7	0.358206	0.879532	2
8	0.376397	0.940257	8	0.178903	0.940257	2
9	0.324318	0.966045	9	0.150035	0.966045	3
10	0.265758	1.000000	10	0.118769	1.000000	3

```

coverage    0.842423
density     0.801915
id           3
mass        0.469484
mean        0.801915
res_dim      2
Name: 3, dtype: object

                box 3
                min    max
2040_H2 Import      0.0 17122.0    [-1.0, 0.00025064668147977375]
2040_demandHinterland 7000.0 20000.0 [6.6175829645645965e-202, 2.11e-321]

```

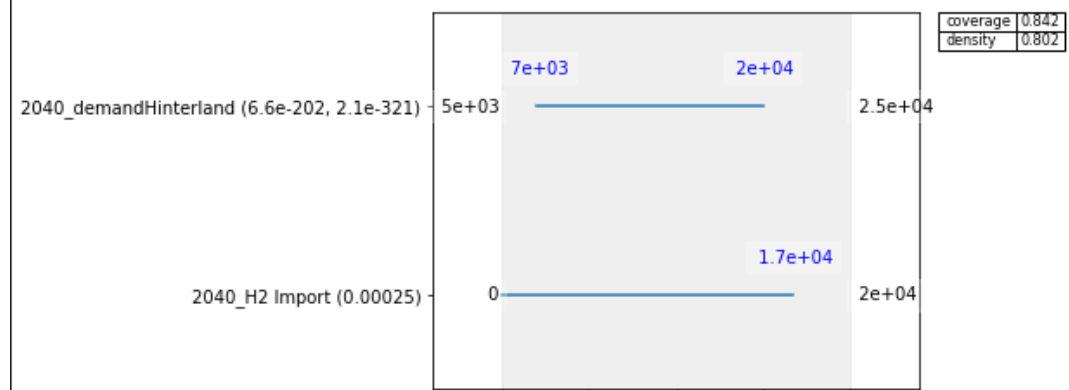
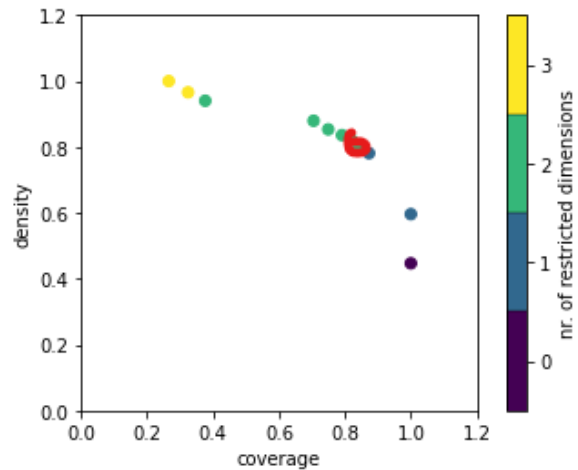


Figure 21: results of the first search round for a PRIM-box in the illustrative example

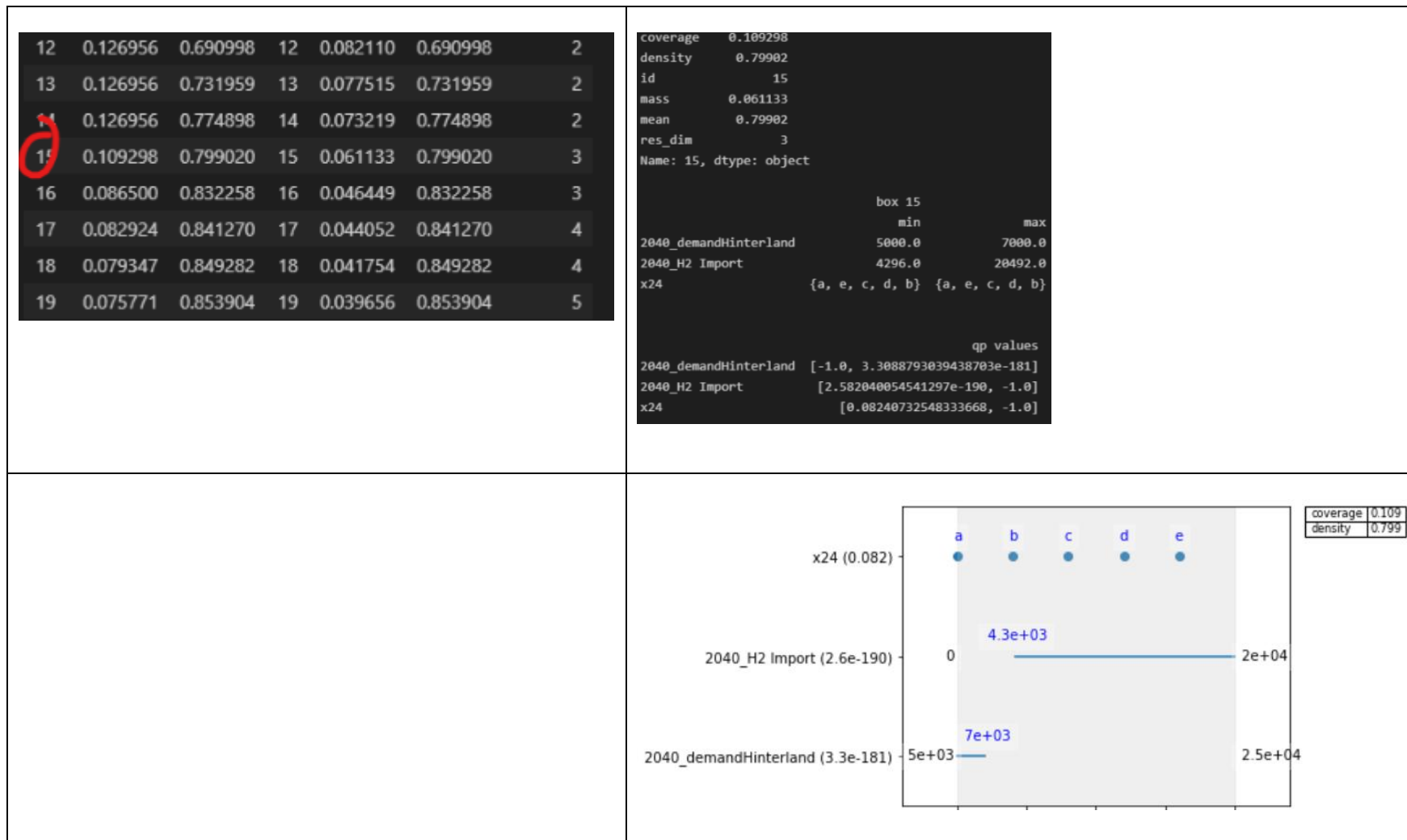


Figure 22: results of the second search round for a PRIM-box in the illustrative example

Synthesis of storylines

The executed PRIM-analyses led to information about which external factors (or dimensions of the scenario space) are dominant in steering the evolution of transport capacity requirements over the planning horizon. Furthermore, information about relevant ranges of values for these external factors was retrieved from these analyses. This information, together with knowledge about the scenario space and coherent energy system model, was used to synthesize storylines of energy system evolution pathways that comprise the main drivers for the evolution of the transport capacity development of the 380 kV- and H₂-network.

6.3.2 Analysis results and discussion

Results PRIM-analysis

During the case study, the analysis team experimented with different set ups of the PRIM-analysis. Different classification methods for data and experiments with data input space (categorical versus ordinal input space) were conducted. The results are summarized in appendix F. In this appendix, also preliminary PRIM-analysis results for the ODO- and NODO- networks have been shown (no further analysis has been conducted for these methane networks).

Results using time series clustering as data classification method

In case the time series were clustered in relatively few groups (three or four), PRIM-analysis revealed drivers from the scenario space that explained the overload patterns of the created time series clusters. For example, PRIM-analysis indicated that the time series cluster with the highest overload values at the end of the planning horizon for the H₂-network, was driven by very strong growth over time of the H₂ demand of the hinterland. Subsequent analysis by grid strategists, confirmed that this result from the PRIM-analysis seemed plausible.

In this case the time clustering algorithm could logically group time series that exhibited a certain order of magnitude of overload at the end of the considered planning horizon (2040 – 2050). Subsequent PRIM-analyses led to insights about drivers for different observed overload patterns in the period from 2040 – 2050. However, no insights about drivers for different overload patterns in the period from 2025 – 2040 were obtained using this method.

In case the time series were clustered into more groups (10 – 12), for various time series clusters no PRIM-box was found. This means that in those cases no drivers from the scenario space could be identified that explained the pattern of the created time series clusters.

A possible explanation for the better results for PRIM-analyses with few time series clusters compared to PRIM-analyses with more time series clusters is the suitability of the applied clustering algorithm in splitting the original dataset into time series with different patterns over time. The time series that were considered comprised six consecutive reference years leading to rather irregular 'spiky' patterns over time. This spikiness in overload patterns might be a cause for the sometimes insufficient performance of the used clustering algorithm in clustering time series with similar patterns. In case time series were split into three to four time series clusters, visual inspection of the resulting clusters revealed that time series clusters had mutually different patterns, especially at the end of the planning horizon. Also, the number of time series that were part of a specific time series cluster (cases) was significant. A significant number of cases is necessary for the PRIM-algorithm to find drivers from the scenario space.

In contrast, splitting of time series in more clusters (10-12 cluster groups) led to several clusters with a low number of cases. Furthermore, visual observation of the obtained clusters suggested that some identified clusters comprised time series with mutually different overload patterns. In future work, it is recommended to investigate the effectivity of other time series clustering algorithms. Also the problem of a too low number of cases of some time series clusters for a proper PRIM-analysis, seems worthwhile to investigate further.

Results using data classification method 'classification per overload class per reference year'

Using the data classification method 'classification per overload class per reference year' for PRIM-analyses led to more insights into drivers for overload development of different order of magnitude in the years 2025- 2040. The obtained results for the H₂-network in the years 2045-2050 showed similar drivers compared to the results obtained with the time series clustering method.

Due to the limited time, no in depth analysis was possible to improve PRIM-analysis results. The executed PRIM-analyses can be seen as a first exploration of the capability of PRIM-analyses to reveal drivers in energy system evolution pathways for specific overload pattern development over time for energy infrastructure.

The obtained results suggest that PRIM-analyses are instrumental in finding drivers from energy system evolution pathways for overload pattern development in energy infrastructure.

Results storyline synthesis

Table 14 highlights the results of the storyline synthesis.

Table 14: developed storyline space for H₂- and 380 kV-networks

Independent storyline subject	Value					# of values of independent storyline subject
1. Growth non-oil based HydroCarbon (HC) production	A. Low, moderate growth of H ₂ import AND/OR low, moderate growth of H ₂ O electrolysis for HC production	B. Strong growth of H ₂ import for synthetic fuel production	C. Very strong growth of H ₂ import for synthetic fuel production	D. Strong growth H ₂ O electrolysis for synthetic fuel production	E. Very strong growth H ₂ O electrolysis for synthetic fuel production	5
2. Growth electrolysis capacity for H ₂ export	A. Low	B. Moderate	C. Strong			3
3. Growth offshore wind landing capacity	A. Low, moderate	B. Strong	C. Very strong			3
4. Growth H ₂ demand hinterland	A. Low	B. Moderate	C. Strong	D. Very strong		4
5. Switch heat supply system built environment towards heat grid and/or electricity driven systems	A. No	B. Yes				2
Total # of storylines						360

The following independent storyline factors, that form the basis for the storyline space, have emerged from this synthesis effort:

1. Growth of non-oil based HydroCarbon (HC) production. This storyline factor represents various main directions of energy system evolution at sites that are part of the HC production subsystem: current oil refineries and a part of Maasvlakte 2. For example value A represents small changes in these subsystem over the planning period. Other values for these storylines represent strong or very strong growth of synthetic fuel production capacity that is either fed with in situ H₂ production via H₂O electrolysis or via seaside H₂ import. Storylines with value D or E can only emerge in case CCS is not implemented in HIC Rotterdam. In case it is certain that CCS will be implemented, storyline D and E are not viable anymore. Integration of CCS leads thus to a path dependency (it prevents emergence of storylines that are build with storyline factor 1 values D and E).

2. Growth of electrolysis capacity for H₂ export. This storyline factor represents various growth scenarios for H₂O electrolysis capacity in HIC Rotterdam of which the produced H₂ is used at other sites in the HIC or is exported to the hinterland.
3. Growth of offshore wind landing capacity. This storyline factor describes various growth scenarios for offshore wind capacity landing in the HIC Rotterdam.
4. Growth of H₂ demand of the hinterland. With this storyline factor various growth scenarios for H₂ demand in the hinterland are described.
5. Switch of heat supply system for the built environment towards a heat grid and /or electricity driven systems. Value B for this storyline factor results in the availability of extra H₂ transport capacity from 2040 onwards by the availability of a current G gas line for H₂ transport. Selection of value A will not lead to a change of the functionality of the current G gas line (i.e., that line will be used for methane transport during the planning horizon).

From the developed storyline space, 360 storylines can be created. The developed visualization tool¹² provides per storyline the following information:

- Overload patterns over time for the 380 kV- and H₂-networks for the scenarios that are part of a storyline.
- 'DNA-map' for these networks in which the overload magnitude in several reference years is expressed with an overload class score for the scenarios that are part of a storyline.
- 'DNA-map' per infrastructure element (380 kV, H₂) in which the overload magnitude in several reference years is expressed with an overload class score for the scenarios that are part of a storyline.
- Overload evolution over time for the 380 kV- and H₂-networks on a geographic map.
- The highest overload score per network (380 kV, H₂) in the period from 2035 onwards for a selected scenario that is part of the storyline. This scenario is selected from the set of scenarios that describe a storyline by taking the scenario with the median overload value in reference year 2045.

6.4 Providing impact of infrastructure information for storylines

Figures 23 and 24 show the bandwidths of overload evolution over the planning horizon for various storylines for the 380 kV- and H₂-network, respectively. The created information can be used to inform a decision-making process on socially desirable long-term energy system evolution pathways with information about the impact of energy infrastructure. Per option for a long-term energy system pathway (storyline) the overload score for the 380 kV- and H₂-network, that represents the impact of energy infrastructure, can be given. Table 15 illustrates the information that is provided for the decision-making on long-term socially desirable energy system evolution pathways. This decision-making process step corresponds to process step 2C of the Gridmaster method.

¹² The visualization tool can be found at <https://public.tableau.com/app/profile/gridmaster2022>

1.1.3 Timeseries Tennet Graph 380KV

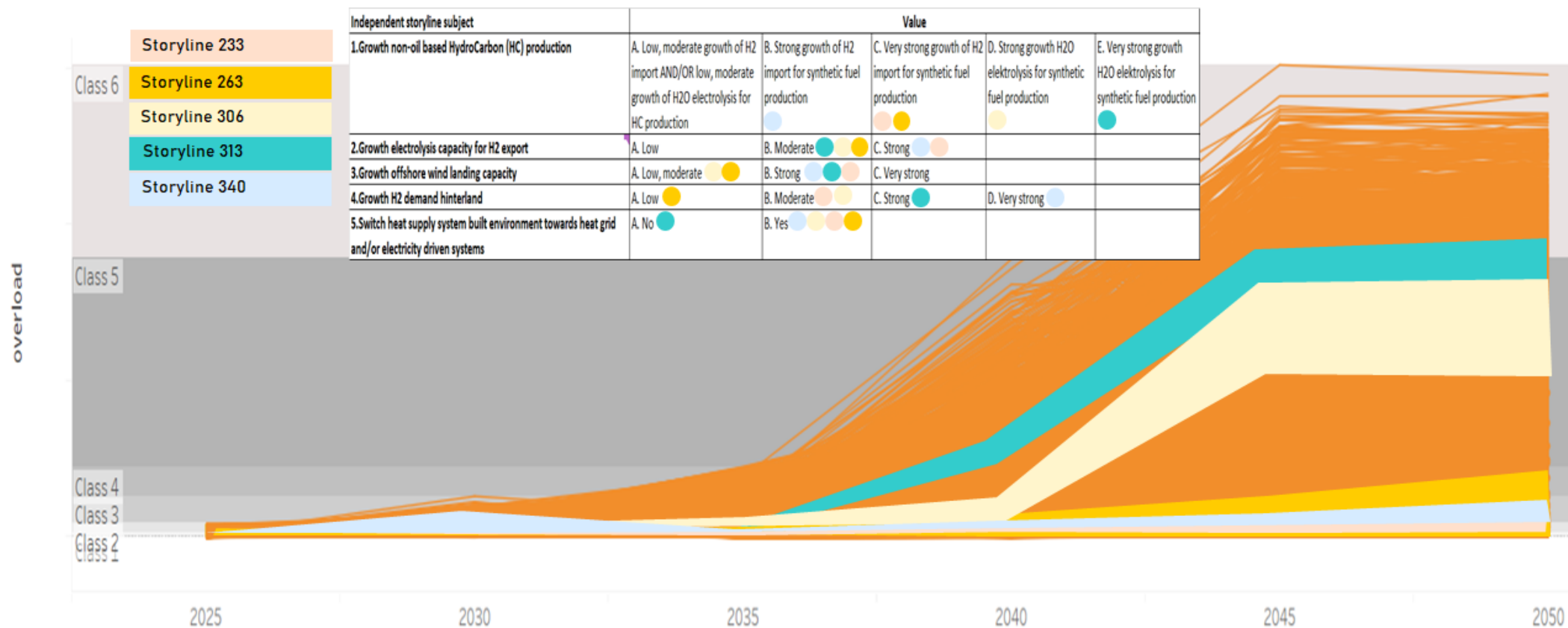


Figure 23 : evolution of overload for the 380 kV-network in various storylines

1.1.4 Timeseries Overload Curve Gasunie Graph H₂- network

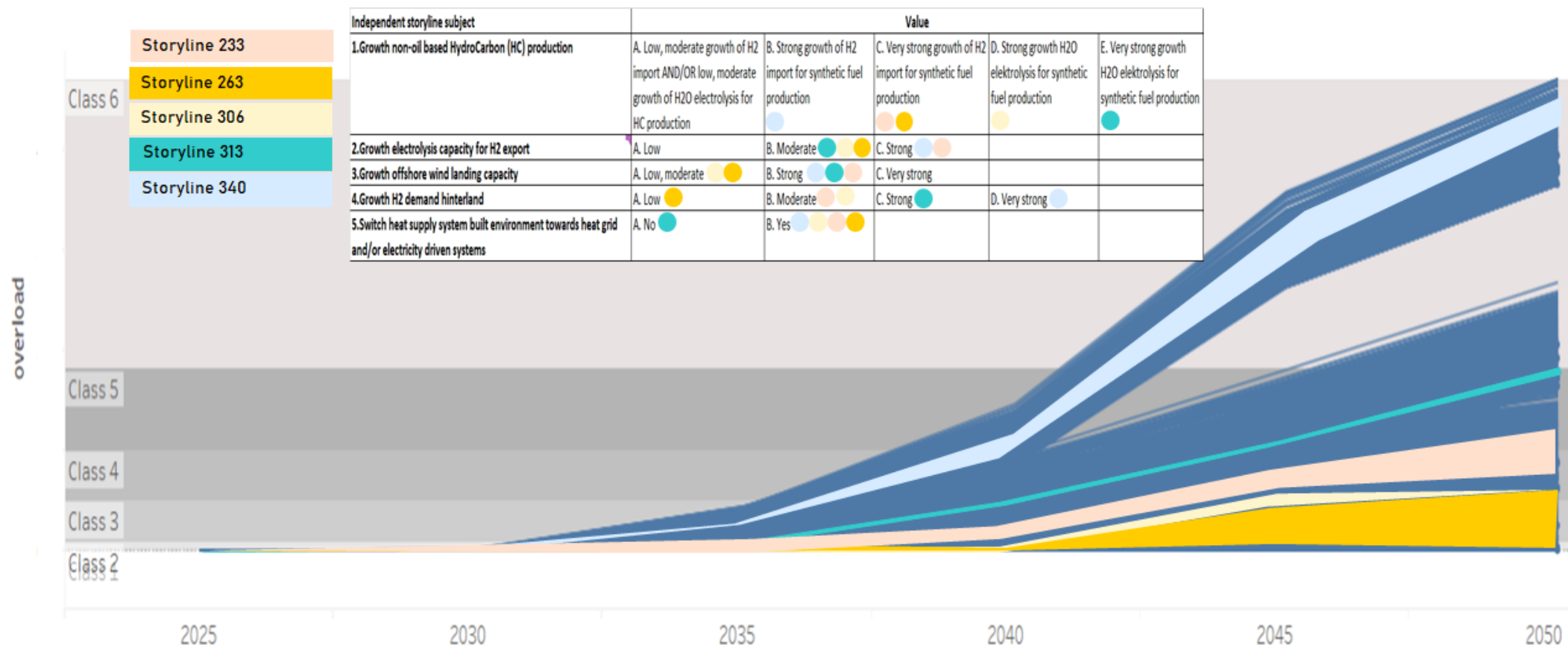


Figure 24 : evolution of overload for the H₂-network in various storylines

Table 15: illustration of provided information about the impact of energy infrastructure on long-term energy system pathways (storylines). See figures 23 and 24 for the description of the storylines for which the impact of energy infrastructure is given.

Storyline	Social benefits / social value	Social cost [overload class]
...	...	380 kV:... ;H ₂ :...
233	...	380 kV:3 ;H ₂ :4
263	...	380 kV:2 ;H ₂ :3
306	...	380 kV:5 ;H ₂ :4
313	...	380 kV:6 ;H ₂ :5
340	...	380 kV:3 ;H ₂ :6
...	...	380 kV:... ;H ₂ :...

7. Development of strategic direction for a robust, adaptive investment path

The objective of part 3 of the Gridmaster method is to develop a strategic direction for a robust, adaptive investment path for integrated infrastructure (see figure 25). Not all process steps of part 3 of the Gridmaster method have been tested in the case study. In this section, the process steps that are tested are described.

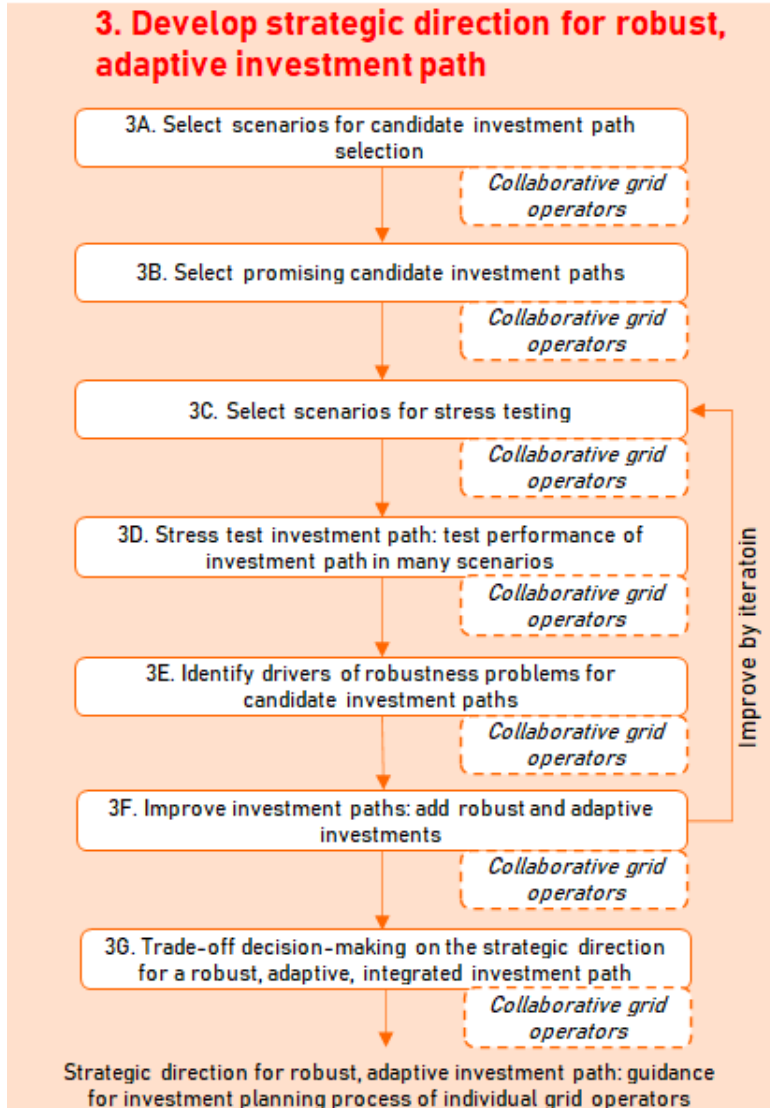


Figure 25: snapshot of the overall Gridmaster process from figure 5 that highlights the process steps for the development of a strategic direction for a robust, adaptive investment path for integrated energy infrastructure

7.1 Stress test of candidate investment path

In the case study, process step 2C (decision-making on socially desirable storylines for energy system evolution) has not been tested. As a consequence, no information about which storylines are socially desirable and which are not was created in the case study. Furthermore, process step 3B (selection of promising candidate investment paths) was not executed in the case study. Instead, the MIEK investment path was chosen as candidate investment path that was stress tested in the case study (process step 3D of Gridmaster method).

The set of scenarios for stress testing was equal to the set that was used for the creation of storyline-overload relations for the indication of impact of energy infrastructure in long-term energy system evolution pathways (see section 6).

After selection of the scenario set for stress testing and the candidate investment path, step 3D of the Gridmaster method was executed in the case study.

The bandwidths of overload patterns over time for the various energy networks are shown in figures 26 - 32. As already mentioned in paragraph 5.3.6, the accuracy of overload calculations is not good enough to draw quantitative conclusions about the robustness performance of the tested investment path. However, the simulation results were good enough to assess the usefulness of the developed method for the creation of a strategic direction for a robust, adaptive investment path of integrated energy infrastructure.

Based on the simulation results, the robustness performance of the MIEK investment path has been calculated (see table 16).

Table 16: Calculated robustness performance of the MIEK investment path (no quantitative conclusions can be drawn, see paragraph 5.3.6).

	% facilitated scenarios	
Network	Short-term KPI	Long-term KPI
380 kV	24%	2%
150 kV	15%	98%
H2	98%	4%
MV	100%	98%
HTLH	100%	96%
NODO	100%	90%
ODO	100%	85%
<i>Integral</i>	<i>3%</i>	<i>0.1%</i>

From table 16, it can be seen that the robustness performances on capacity (both short-term and long-term) are lower for the integrated investment path compared to the performances for the individual energy networks. This is caused by the fact that drivers in energy system evolution pathways for overload growth in the various energy networks differ. For example, a huge growth of H₂ import will lead to a growth in overload magnitude for the H₂-network, but will not affect the overload magnitude development in the electricity networks. This observation confirms the added value of coordination of long-term investment planning for the individual energy networks.

1.1.2 Timeseries Distribution MIEK 380KV

Overload class	2025	2030	2035	2040	2045	2050
1	32.7%	11.1%	25.5%	13.3%	4.3%	2.5%
2	67.3%	51.7%	35.4%	25.4%	17.1%	14.4%
3		37.2%	32.6%	32.4%	31.0%	30.6%
4		0.0%	6.5%	14.3%	18.6%	21.2%
5			0.0%	14.5%	25.1%	27.1%
6					3.9%	4.2%

1.1.3 Timeseries Graph 380KV

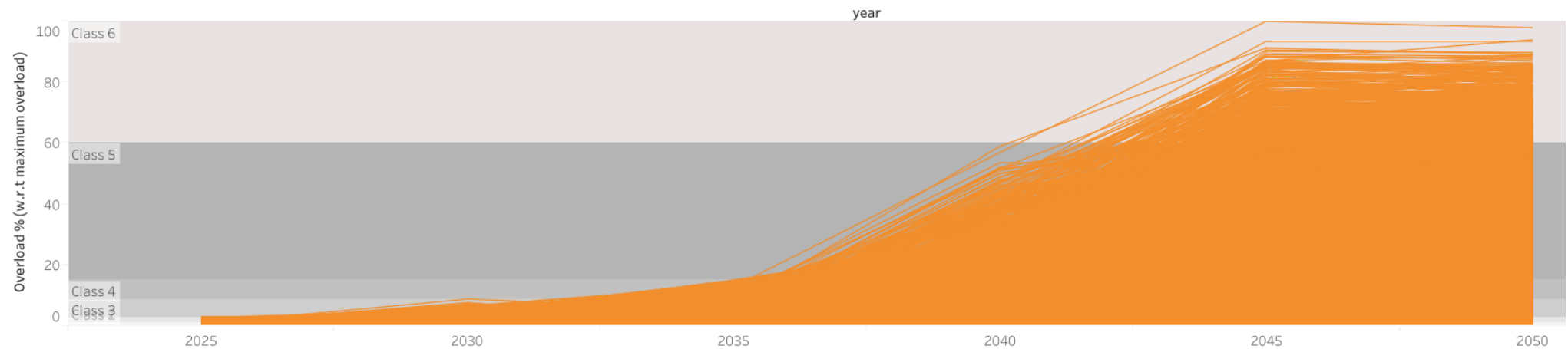


Figure 26: obtained simulation results for the overload evolution over time for the 380 kV-network in 9,980 scenarios. In the table the percentages of scenarios in the various overload classes have been shown for the various reference years. As mentioned in paragraph 5.3.6, the absolute values for the calculated overloads are not accurate enough for quantitative conclusions.

1.1.2 Timeseries TenneT Distribution MIEK 150KV

Overload sc.,	year					
	2025	2030	2035	2040	2045	2050
1	60,3%	15,6%	97,3%	97,5%	97,3%	97,5%
2	2,2%	9,0%	2,7%	2,5%	2,7%	2,5%
3		18,0%				
4	37,5%	41,3%				
5		16,1%				

1.1.3 Timeseries Tennes Graph 150KV

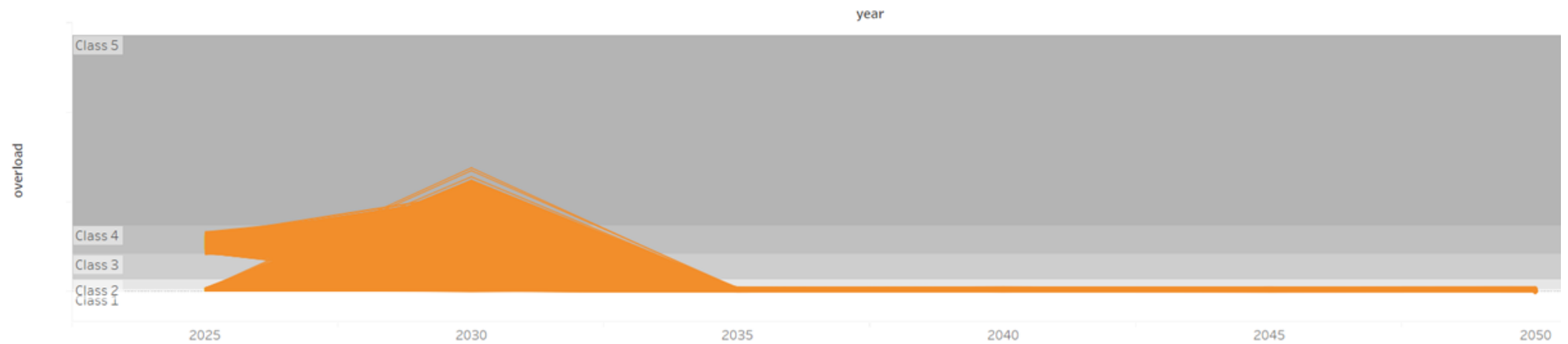


Figure 27: obtained simulation results for the overload evolution over time for the 150 kV-network in 9,980 scenarios. In the table the percentages of scenarios in the various overload classes have been shown for the various reference years. As mentioned in paragraph 5.3.6, the absolute values for the calculated overloads are not accurate enough for quantitative conclusions.

1.1.2 Timeseries Medium Voltage

Overload sc..	year					
	2025	2030	2035	2040	2045	2050
1	100,0%	100,0%	89,8%	92,4%	93,5%	98,0%
2			0,2%	0,9%	1,2%	0,9%
3			4,0%	5,0%	3,5%	0,7%
4			6,0%	1,6%	1,8%	0,4%

1.1.3 Timeseries Medium Voltage

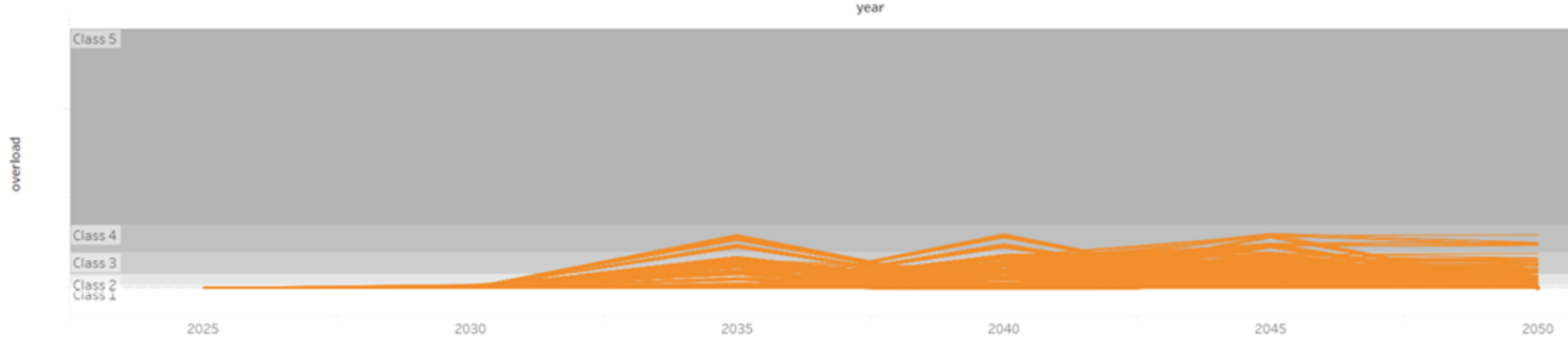
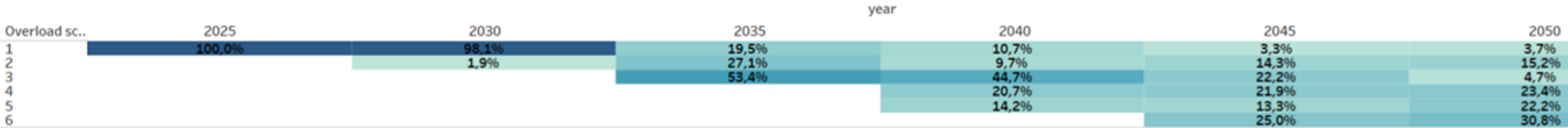


Figure 28: obtained simulation results for the overload evolution over time for the Medium Voltage-network in 9,980 scenarios. In the table the percentages of scenarios in the various overload classes have been shown for the various reference years. As mentioned in paragraph 5.3.6, the absolute values for the calculated overloads are not accurate enough for quantitative conclusions.

1.1.2 Timeseries Gasunie H2 Distribution MIEK



1.1.4 Timeseries Overload Curve Gasunie Graph

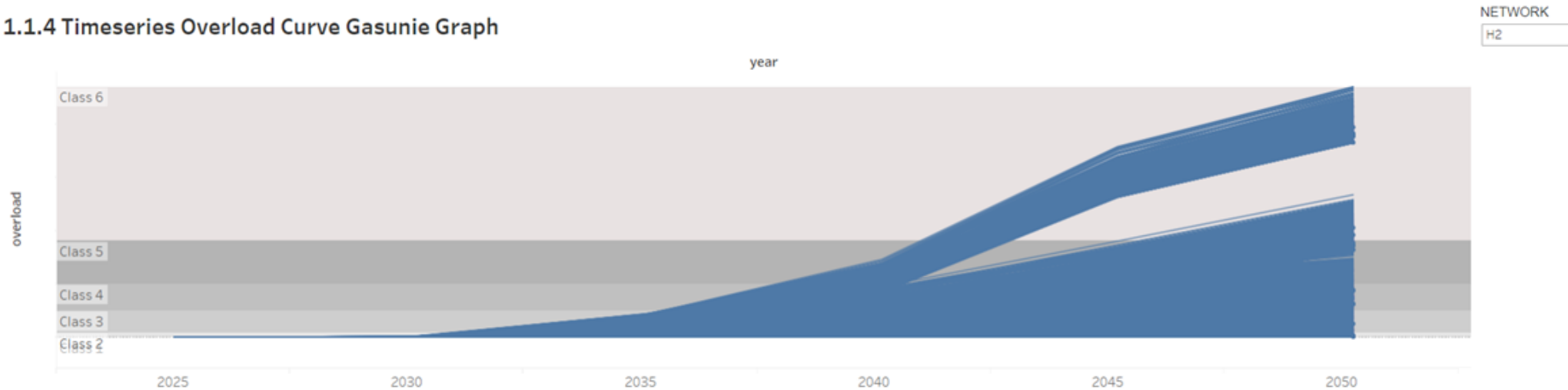


Figure 29: obtained simulation results for the overload evolution over time for the H₂-network in 9,980 scenarios. In the table the percentages of scenarios in the various overload classes have been shown for the various reference years. As mentioned in paragraph 5.3.6, the absolute values for the calculated overloads are not accurate enough for quantitative conclusions.

Overload sc..	2025	2030	2035	2040	2045	2050
1	100,0%	100,0%	99,7%	98,0%	96,3%	95,5%
2			0,3%	2,0%	3,7%	4,5%
3		0,0%				

1.1.4 Timeseries Overload Curve Gasunie Graph

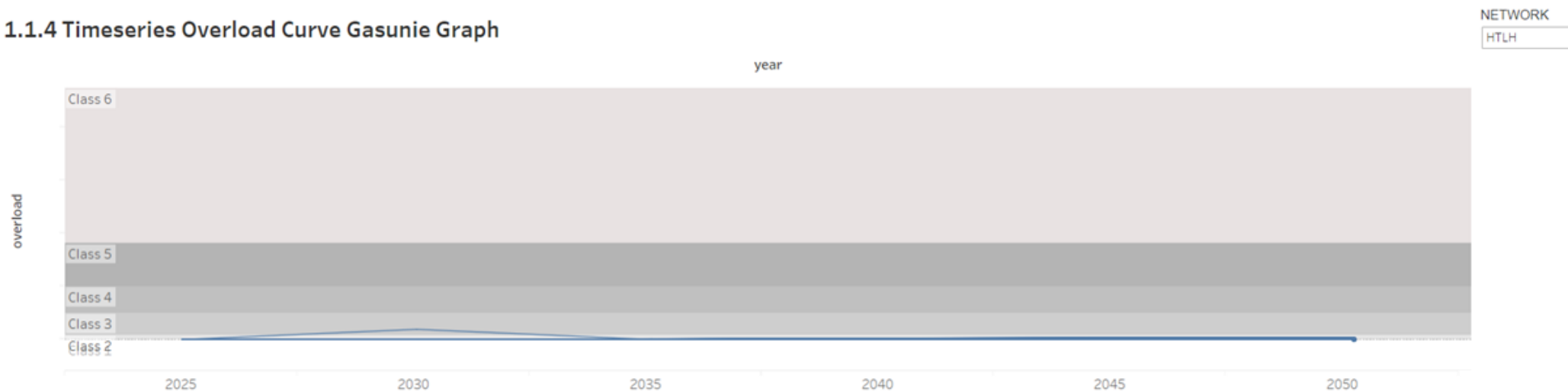


Figure 30: obtained simulation results for the overload evolution over time for the HTLH-network in 9,980 scenarios. In the table the percentages of scenarios in the various overload classes have been shown for the various reference years. As mentioned in paragraph 5.3.6, the absolute values for the calculated overloads are not accurate enough for quantitative conclusions.

Overload sc..	2025	2030	2035	2040	2045	2050
1	100,0%	100,0%	97,6%	92,0%	87,2%	85,4%
2		0,0%	2,4%	7,9%	12,4%	13,8%
3				0,1%	0,4%	0,8%

1.1.4 Timeseries Overload Curve Gasunie Graph

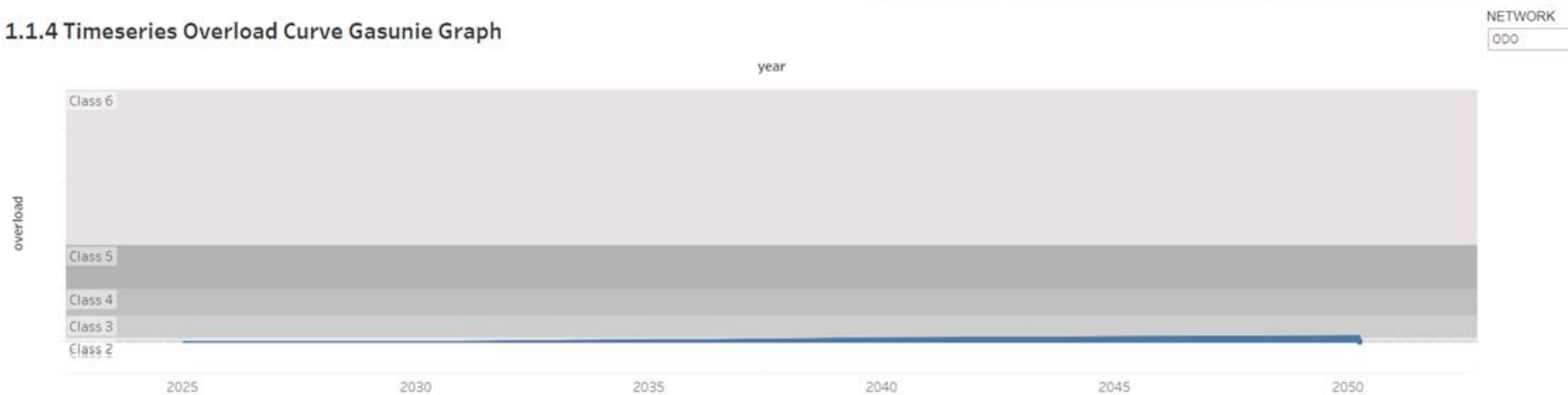


Figure 31: obtained simulation results for the overload evolution over time for the ODO-network in 9,980 scenarios. In the table the percentages of scenarios in the various overload classes have been shown for the various reference years. As mentioned in paragraph 5.3.6, the absolute values for the calculated overloads are not accurate enough for quantitative conclusions.

Overload sc..	2025	2030	2035	2040	2045	2050
1	100,0%	100,0%	95,7%	92,7%	88,1%	90,3%
2			4,3%	7,3%	11,9%	9,7%

1.1.4 Timeseries Overload Curve Gasunie Graph

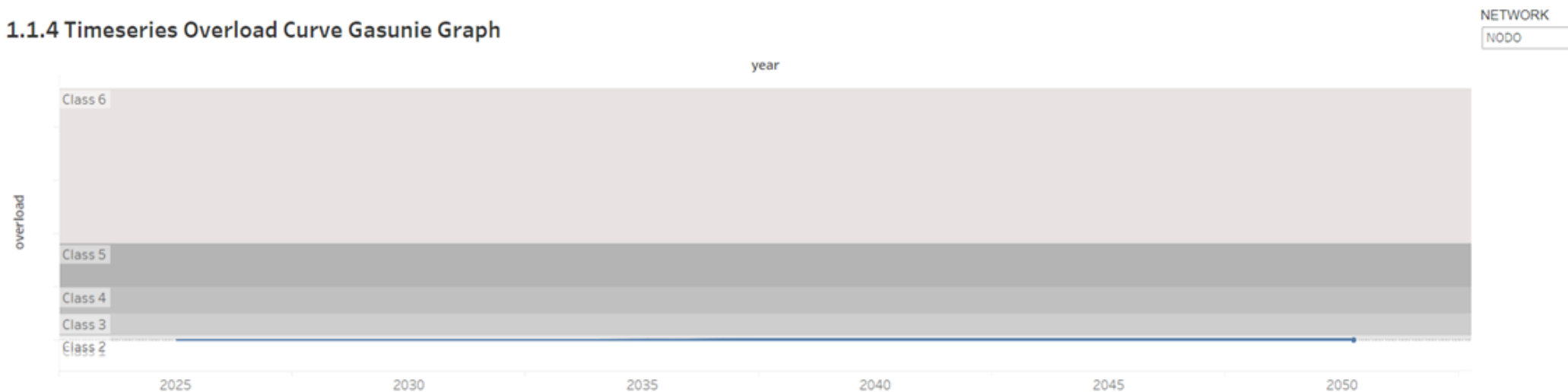


Figure 32: obtained simulation results for the overload evolution over time for the NODO-network in 9,980 scenarios. In the table the percentages of scenarios in the various overload classes have been shown for the various reference years. As mentioned in paragraph 5.3.6, the absolute values for the calculated overloads are not accurate enough for quantitative conclusions.

7.2 Identification of options for the robustness performance improvement of the investment path

Process steps 3E and 3F of the Gridmaster are aimed at identifying options for the improvement of the robustness performance of the candidate investment path. In the case study, these steps have been (partially) executed for the 380 kV- and H₂-networks. Furthermore, options for robustness performance improvement of the Medium Voltage network have been examined in the case study. Below, the results for both analyses have been described.

7.2.1 Options for robustness improvement of the 380 kV- and H₂-network

Identification of drivers for robustness problems

In step 3E of the Gridmaster method, the objective is to identify the main drivers for the future overload evolution in the considered energy networks. In other words, the objective is to find storyline-overload relations in order to enable the identification of adaptive investments that improve the robustness performance of the investment path.

The storyline-overload relations for the 380 kV- and H₂-network, described in paragraph 6.3.2, can be reused. This information can be reused since the same investment path and same set of scenarios was used for both the exploration of overload development of the current investment path (step 2A of the Gridmaster method) and the stress testing of the candidate investment path (step 3D of the Gridmaster method).

Options for additional robust and adaptive investments

380 kV-network

The overload pattern for the 380 kV-network shows scenarios for which the overload is higher than overload class 1 in reference years 2025 and 2030. However, it is impossible to increase the transport capacity of this network before 2030 due to the long lead times for the realization of capacity expansion investments. Therefore, to support the assessment of the capability of the Gridmaster method in identifying robust and adaptive investments, the overload pattern for the 380 kV-network was manipulated for the reference years 2025 and 2030. The data with overload classes > 1 have been removed, which resulted in figure 33.

Options for robust investments

In reference year 2035, a part of the scenarios lead to overload magnitudes in overload classes > 1. Therefore, additional robust investments are necessary to facilitate all scenarios for the short-term. These investments should be planned in the short-run for on time realization of the necessary extra transport capacity.

For reference year 2035, a so-called 'DNA-map' has been made that shows the overload magnitude of energy infrastructure elements across the set of scenarios (see figure 34). This map provides insights into the contribution of individual infrastructure elements to the overload magnitude of the 380 kV-network across the evaluated scenarios.

1.1.3 Timeseries Tennet Graph 380KV

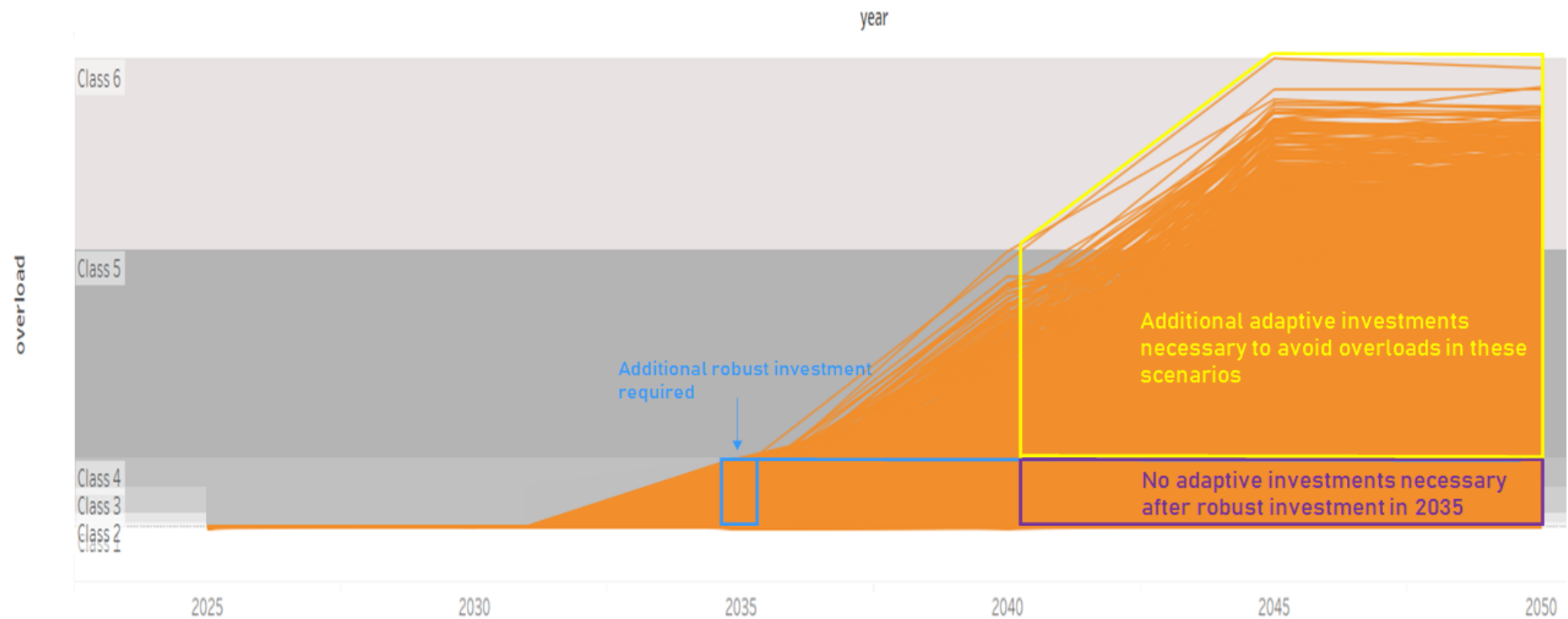


Figure 33: adjusted overload pattern for the 380 kV-network (data with overload class > 1 in reference years 2025 and 2030 have been removed).

Gridmaster | 1.4 MIEK DNA Infra Elements

1.1.4 MIEK DNA Map Infra Elements 2035

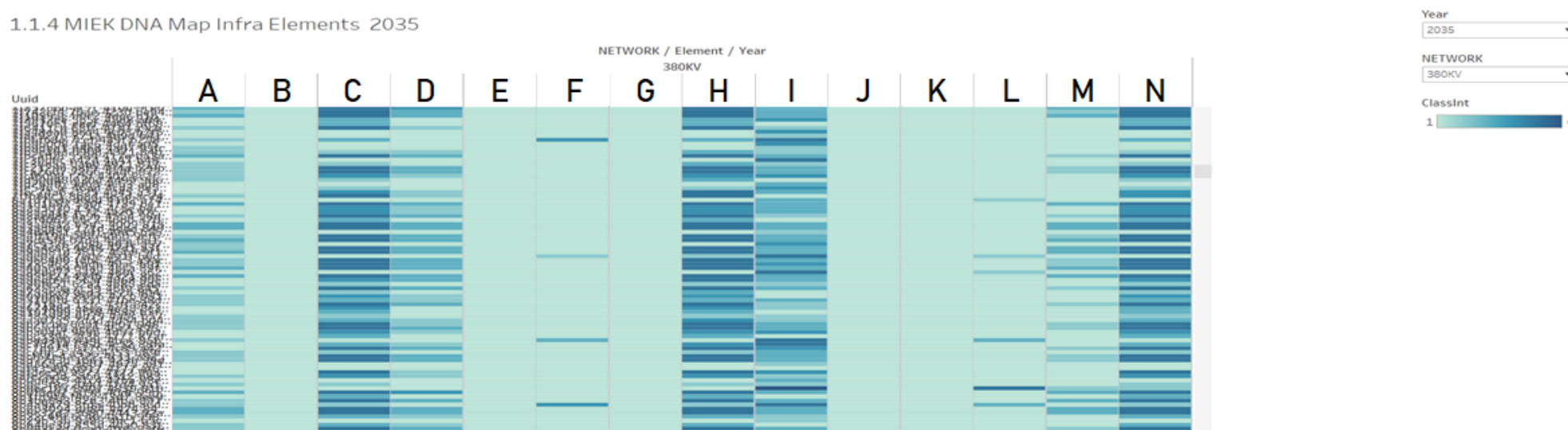


Figure 34: Part of the DNA-map for infrastructure elements of the 380 kV-network in 2035. On the y-axis scenario IDs are shown. On the x-axis the infrastructure elements are shown. Per scenario ID per infrastructure element the overload magnitude (via overload classes) is shown via a color scale. The darker the color, the higher the overload class.

The following information can be retrieved from figure 34:

1. Infrastructure elements B, E, G, J, and K are not critically overloaded across the evaluated scenarios, *i.e.* the overloads fall into overload class 1.
2. A low percentage of scenarios leads to overload class >1 for infrastructure elements F and L.
3. A relatively high percentage of scenarios gives rise to an overload class > 1 for infrastructure elements A, C, D, H, I, M and N. For elements C, H and N, a relatively high percentage of scenarios gives rise to an overload class > 3.

These observations support the assessment by grid strategists of effective options for additional robust investments to increase the short-term robustness performance on capacity for the investment path. The effectivity of the potential options should be verified in a next round of simulations in which the options for adjusted candidate investment paths are stress tested.

Options for adaptive investments

After 2035, a part of the scenarios lead to a strong growth in overload magnitude while other scenarios result in relatively low overload magnitudes in the period from 2040 - 2050. Under the assumption of a realized robust investment package in 2035, two overload regions can be identified. The first overload region is the region for which adaptive investments after 2035 are necessary. The other overload region does not require adaptive investments (see figure 33).

The obtained storylines for the 380 kV- and H₂-network (see table 14) have been used to find the drivers for adaptive investments for the 380 kV-network. This was done by conducting PRIM-analyses, in which the input space comprised the storyline space and the output of interests comprised a set of storylines with a certain overload class value in 2050.

Table 17 summarizes the results of the conducted PRIM-analyses. Drivers for adaptive investments comprise always a combination of various storyline factors. Three drivers have been found for overload evolution towards overload class 5 in 2050 (see table 18). The coverage of these drivers is 81%, meaning that 81% of scenarios that end with overload class 5 in 2050 are a result of these drivers. Two drivers have been identified for overload evolution towards overload class 6. These drivers have a high coverage of 95%. The coverage for drivers that lead to overload classes 5 and 6 is satisfactorily high. The storyline drivers constitute two or three storyline factors.

Table 17: summary of PRIM-analyses for identification of storyline drivers of adaptive investments for the 380 kV-network

Overload class in 2050	Storyline driver for long-term overload class	Coverage / density of found PRIM-boxes
2	1) Very strong growth of H ₂ import for synthetic fuel production & 2) Moderate / strong growth of H ₂ O electrolysis capacity for H ₂ -export & 3) Low growth of offshore wind	0,48 / 0,8
	1) Strong growth of H ₂ import for synthetic fuel production & 3) Low growth of offshore wind	0,22 / 1
3	1) No strong / very strong growth of H ₂ O electrolysis capacity for synthetic fuel production & 2) Strong growth of H ₂ O electrolysis capacity for H ₂ -export & 3) Strong growth of offshore wind	0,29 / 1
	1) Low / moderate growth of H ₂ import AND / OR low / moderate growth of H ₂ O electrolysis capacity for hydrocarbon production & 3) Low / moderate growth of offshore wind	0,19 / 0,8
	1) Strong / very strong growth of H ₂ import for synthetic fuel production & 2) Low growth of H ₂ O electrolysis capacity for H ₂ -export & 3) Low / moderate growth of offshore wind	0,13 / 0,8

Overload class in 2050	Storyline driver for long-term overload class	Coverage / density of found PRIM-boxes
3	1) Strong growth of H ₂ import for synthetic fuel production & 2) Moderate growth of H ₂ O electrolysis capacity for H ₂ -export	0,06 / 0,8
4	1) Low / moderate growth of H ₂ import AND / OR low / moderate growth of H ₂ O electrolysis capacity for hydrocarbon production & 2) Strong growth of H ₂ O electrolysis capacity for H ₂ -export & 3) Very strong growth of offshore wind	0,17 / 1
	1) Strong growth of H ₂ import for synthetic fuel production & 3) Very strong growth of offshore wind	0,08 / 1
	1) Low / moderate growth of H ₂ import AND / OR low / moderate growth of H ₂ O electrolysis capacity for hydrocarbon production & 2 Low / moderate growth of H ₂ O electrolysis capacity for H ₂ -export & 3) Strong growth of offshore wind	0,08 / 1
5	1) Low / moderate growth of H ₂ import AND / OR low / moderate growth of H ₂ O electrolysis capacity for hydrocarbon production & 2) Low growth of H ₂ O electrolysis capacity for H ₂ -export & 3) Strong / very strong growth of offshore wind	0,38 / 0,9
	1) Strong growth of H ₂ O electrolysis capacity for synthetic fuel production & 2) Moderate / strong growth of H ₂ O electrolysis capacity for H ₂ -export	0,3 / 1

Overload class in 2050	Storyline driver for long-term overload class	Coverage / density of found PRIM-boxes
5	<p>1) <u>No</u> low / moderate growth of H₂ import AND / OR low / moderate growth of H₂O electrolysis capacity for hydrocarbon production & <u>no</u> Strong growth of H₂O electrolysis capacity for synthetic fuel production &</p> <p>2) Moderate growth of H₂O electrolysis capacity for H₂-export &</p> <p>3) Very strong growth of offshore wind</p>	0,13 / 0,8
6	<p>1) Very strong growth of H₂O electrolysis capacity for synthetic fuel production &</p> <p>2) Moderate / strong growth of H₂O electrolysis capacity for H₂-export</p>	0,84 / 0,8
	<p>1) Very strong growth of H₂O electrolysis capacity for synthetic fuel production &</p> <p>2) Low growth of H₂O electrolysis capacity for H₂-export &</p> <p>3) Low / moderate growth of offshore wind</p>	0,11 / 0,8

Table 18: overview of the identified numbers of storyline drivers and the coverage of found PRIM-boxes for the 380 kV-network for overload classes > 4 in 2050

Overload class in 2050	Number of drivers	Cumulative coverage of PRIM-boxes
5	3	81%
6	2	95%

The 'DNA-map' functionality in the visualization tool can be used to understand what the overload of infrastructure elements will be in case a certain driver for storylines becomes reality. For illustration of this functionality, figures 35 and 36 show the DNA-maps for the infrastructure elements for four storylines that are part of storyline driver 'combination of very strong growth of H₂O electrolysis capacity for synthetic fuel production AND moderate / strong growth of H₂O electrolysis capacity growth for H₂-export'.

These DNA-maps show the overload pattern evolution over time for energy infrastructure elements across the scenarios. These patterns can inform grid strategists about adaptive investment options that might be valuable in case the driver "combination of very strong growth of H₂O electrolysis capacity for synthetic fuel production AND moderate / strong growth of H₂O electrolysis capacity growth for H₂-export" might become reality. Part of an adaptive investment package to mitigate overload situations in case this storyline driver becomes reality are probably investments in infrastructure elements C, F, H, I, L, N and O. Reason for this is that these infrastructure elements have overload classes of 5 or 6 in 2050 across all explored scenarios that belong to the storyline driver.

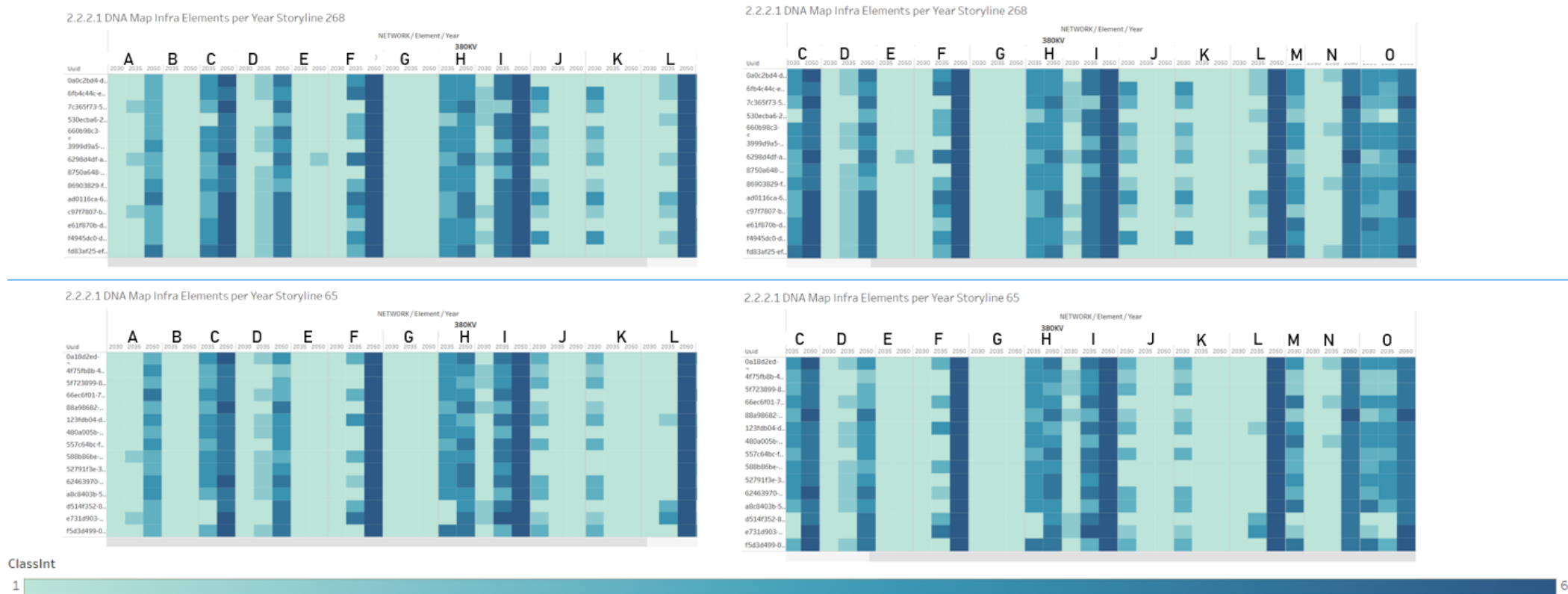
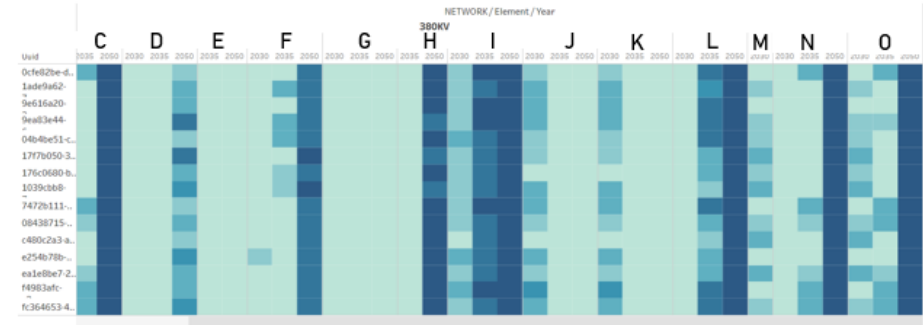


Figure 35: illustration of the overload magnitude evolution for energy infrastructure elements of the 380 kV-network of storylines that are part of the storyline driver “combination of very strong growth of H₂O electrolysis capacity for synthetic fuel production AND moderate / strong growth of H₂O electrolysis capacity growth for H₂-export”.

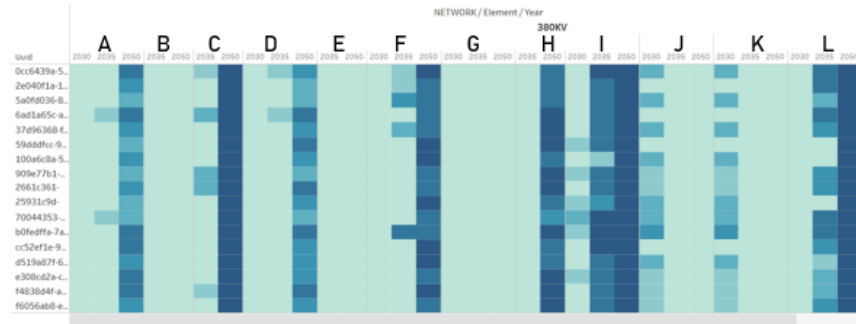
2.2.2.1 DNA Map Infra Elements per Year Storyline 27



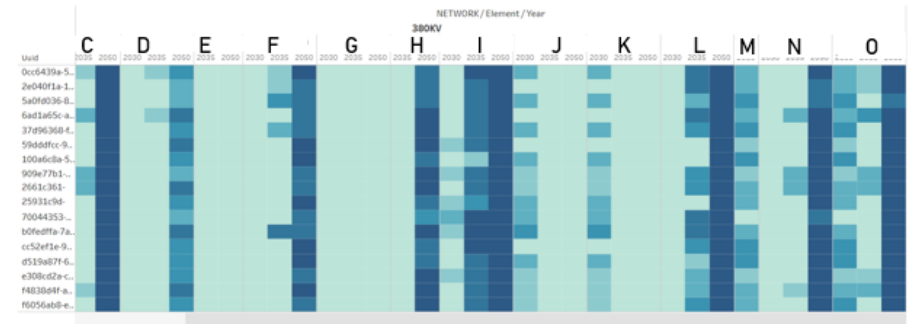
2.2.2.1 DNA Map Infra Elements per Year Storyline 27



2.2.2.1 DNA Map Infra Elements per Year Storyline 235



2.2.2.1 DNA Map Infra Elements per Year Storyline 235



ClassInt



Figure 36: illustration of the overload magnitude evolution for energy infrastructure elements of the 380 kV-network of storylines that are part of the storyline driver "combination of very strong growth of H₂O electrolysis capacity for synthetic fuel production AND moderate / strong growth of H₂O electrolysis capacity growth for H₂-export".

H₂-network

No robust investments are necessary to improve the short-term performance on capacity for the H₂-network. However, adaptive investments are necessary to cope with scenarios that lead to overload classes > 1 after 2030 (see figure 37).

Options for adaptive investments

In an analogous analysis approach, drivers for storylines have been identified that lead to certain overload classes of the H₂-network in the long run (see tables 19 and 20). The identified drivers for storylines that lead to overload classes > 1 in 2050 have PRIM-box coverages between 75% - 98%. This means that $\geq 75\%$ of the scenarios that lead to overload classes > 1 can be explained by the diagnosed storyline drivers. These coverage values seem acceptably high. The storyline drivers constitute between one and four storyline factors.

Via the visualization tool, DNA-maps for H₂ infrastructure elements are available for storylines that are part of a storyline driver. This is illustrated in figures 38 and 39.

1.1.4 Timeseries Overload Curve Gasunie Graph H₂-network

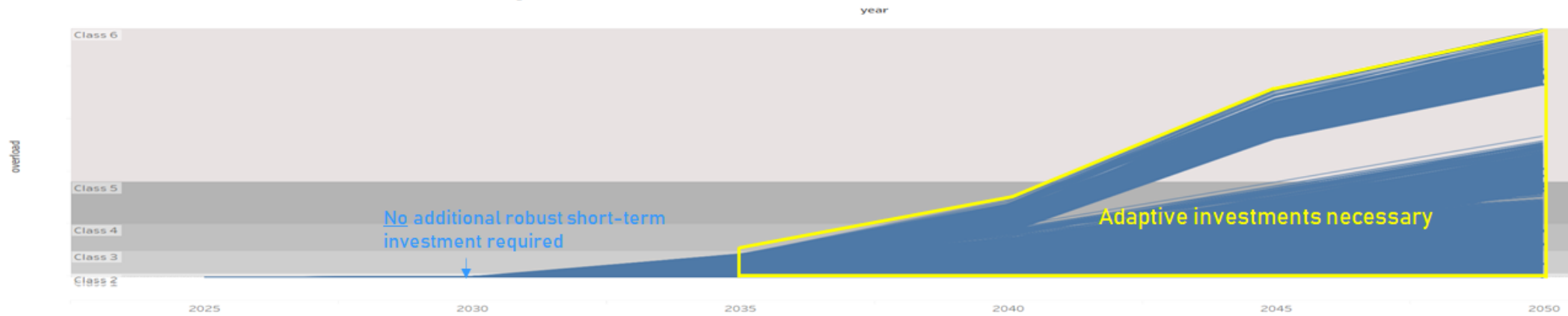


Figure 37: overload pattern for the H₂-network

Table 19: summary of PRIM-analyses for the identification of drivers of adaptive investments for the H₂-network

Overload class in 2050	Storyline driver for long-term overload class	Coverage / density of found PRIM-boxes
1	1) <u>No</u> strong / very strong growth of H ₂ import for synthetic fuel production & 4) Low growth of H ₂ -demand to the hinterland & 5) Switch of built environment towards electricity / heat grid	0,5 / 1
	2) Moderate growth of H ₂ O electrolysis capacity for H ₂ -export & 4) Low growth of H ₂ -demand to the hinterland	0,17 / 0,8
2	1) <u>No</u> very strong growth of H ₂ import for synthetic fuel production & 4) Low growth of H ₂ -demand to the hinterland & 5) <u>No</u> switch of built environment towards electricity / heat grid	0,68 / 0,9
	1) <u>No</u> strong / very strong growth of H ₂ import for synthetic fuel production & 2) Strong growth of H ₂ O electrolysis capacity for H ₂ -export & 4) Low growth of H ₂ -demand to the hinterland & 5) Switch of built environment towards electricity / heat grid	0,18 / 1

Overload class in 2050	Storyline driver for long-term overload class	Coverage / density of found PRIM-boxes
3	1) <u>V</u> ery strong growth of H ₂ import for synthetic fuel production & 4) Low growth of H ₂ -demand to the hinterland	0,75 / 0,8
4	4) Moderate growth of H ₂ -demand to the hinterland	0,98 / 0,9
5	1) <u>N</u> o very strong growth of H ₂ import for synthetic fuel production & 4) Strong growth of H ₂ -demand to the hinterland	0,88 / 0,9
6	4) Very strong growth of H ₂ -demand to the hinterland	0,79 / 1

Table 20: overview of the identified numbers of storyline drivers and the coverage of found PRIM-boxes for the H₂-network for overload classes > 1 in 2050

Overload class in 2050	Number of drivers	Cumulative coverage of PRIM-boxes
2	2	86%
3	1	75%
4	1	98%
5	1	88%
6	1	79%

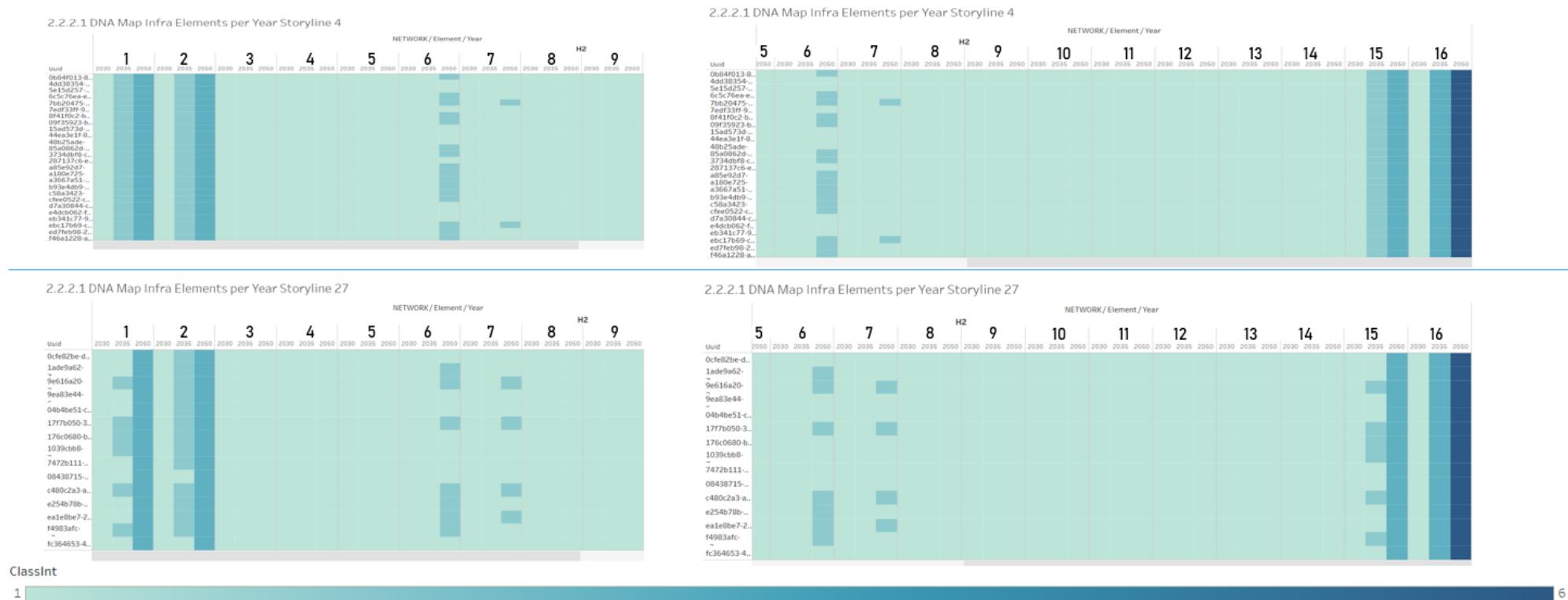
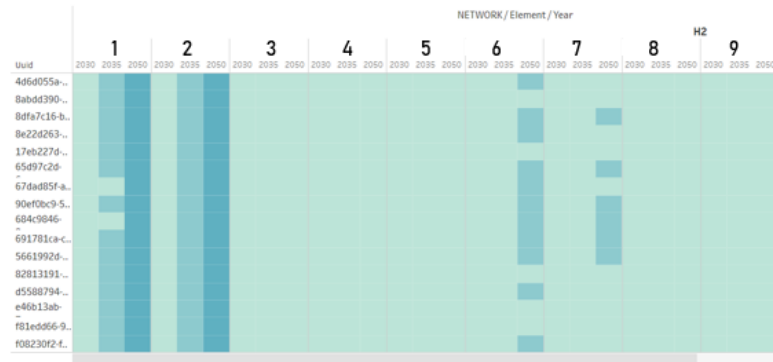
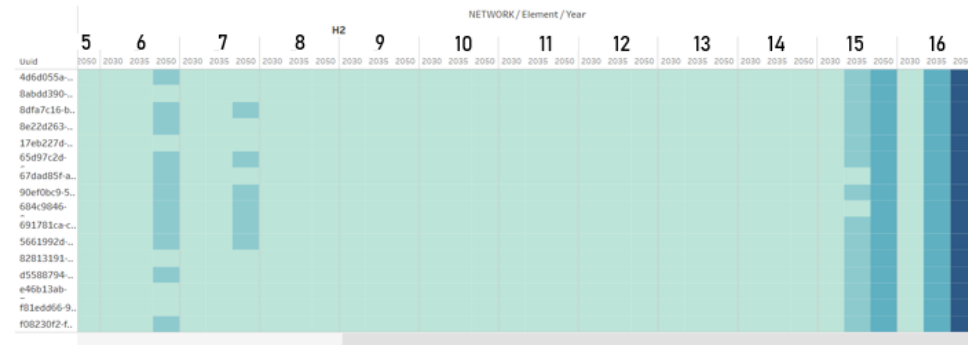


Figure 38: illustration of the overload magnitude evolution for energy infrastructure elements of the H₂-network of storylines that are part of the storyline driver “moderate growth of H₂ demand to the hinterland”.

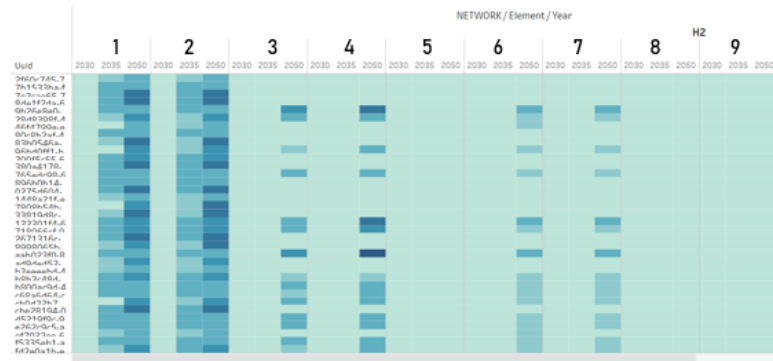
2.2.2.1 DNA Map Infra Elements per Year Storyline 83



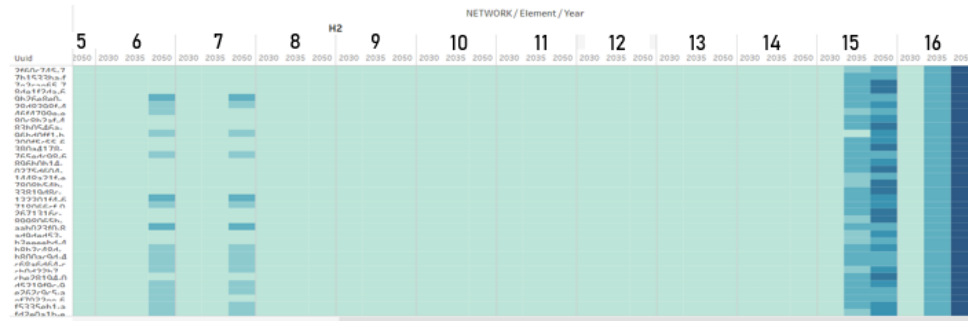
2.2.2.1 DNA Map Infra Elements per Year Storyline 83



2.2.2.1 DNA Map Infra Elements per Year Storyline 136



2.2.2.1 DNA Map Infra Elements per Year Storyline 136



ClassInt



Figure 39: illustration of the overload magnitude evolution for energy infrastructure elements of the H₂-network of storylines that are part of the storyline driver “moderate growth of H₂ demand to the hinterland”.

Summary

Figures 40 and 41 summarize the process steps executed to obtain insights into overload magnitudes that need to be mitigated with robust no regret investments and storyline drivers for the transport capacity evolution towards specific long-term overload magnitudes. For the 380 kV-network robust no regret investments are required to mitigate overloads with overload class level 4 that might occur on the short-term. On the contrary, for the H₂-network no robust investments appear to be necessary to obtain sufficient transport capacity on the short-term.

For the 380 kV- and H₂-network in total 11 storyline drivers have been identified. These storyline drivers are the adaptation tipping point conditions for which specific adaptive investment packages should be designed. In case the energy system evolution progresses into the direction of adaptation tipping point conditions, the linked adaptive investment package should be planned. An individual storyline driver comprises a subset of scenarios, showing the range of overload evolution over time for this storyline driver. 'DNA-maps', showing the range of overload evolution over time for the storyline driver, support the identification of options for an adaptive investment package that prevents overloads in case the storyline driver becomes reality.

It should be noted that it is impossible, with the current investment planning practice, to identify these 11 storyline drivers as scenario points. Especially, since several of these storyline drivers consist of combined developments of different external factors, such as the combined development of a very strong growth of H₂ import for synthetic fuel production with a low growth of H₂ hinterland demand that is a storyline driver for H₂ transport capacity demand evolution into overload class 3 in the long run. Furthermore, the identification of the possible range for short-term overload magnitudes, relevant for the planning of robust no regret investments, is more accurate compared to the current investment planning practice due to the use of many more scenarios in the exploration of the effectivity of an investment path.

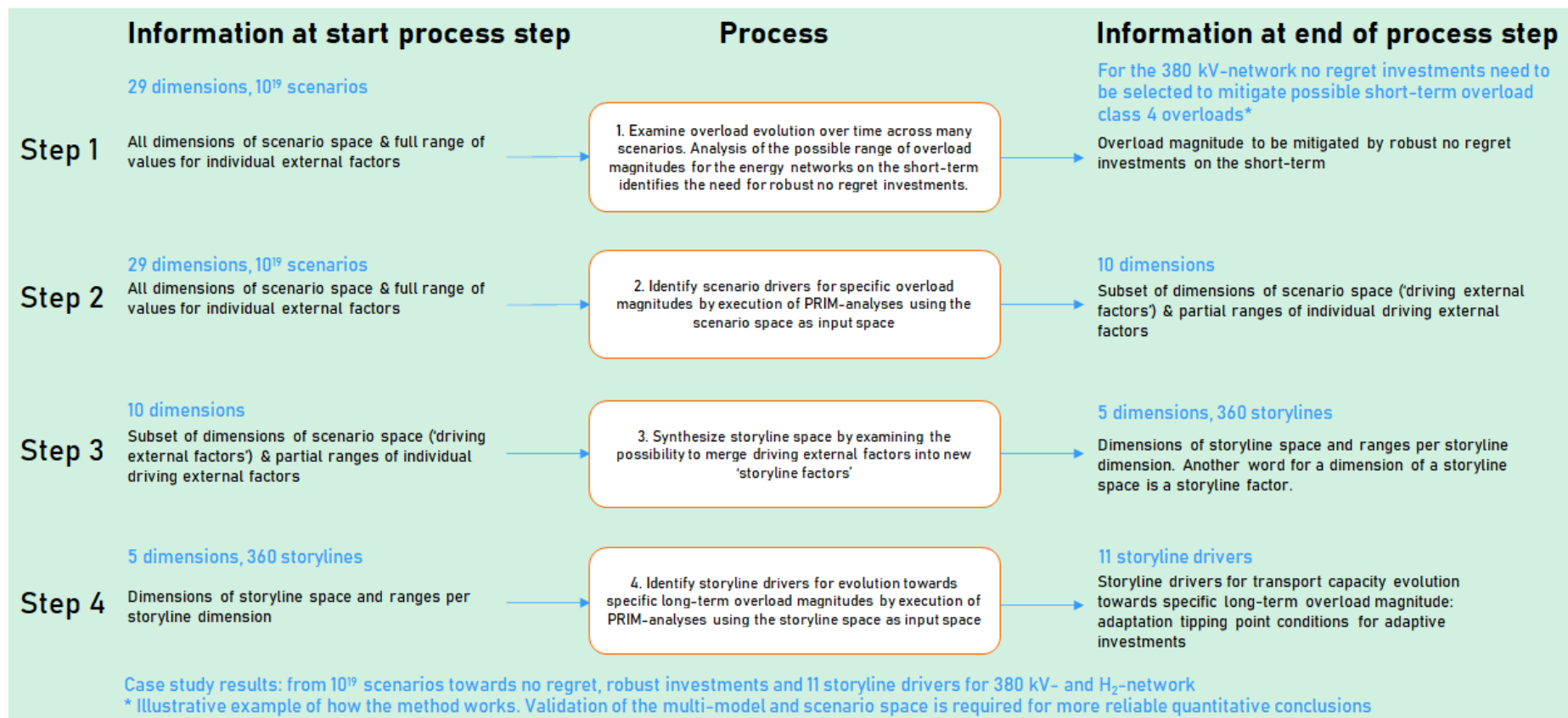


Figure 40: summary of the executed process steps for the identification of robust, no regret investments and 11 storyline drivers, relevant for long-term adaptive investments for the 380 kV- and H₂-network, from an initial scenario space comprising 10¹⁹ scenarios. It should be noted that step 3 was not discussed in a broad expert group.

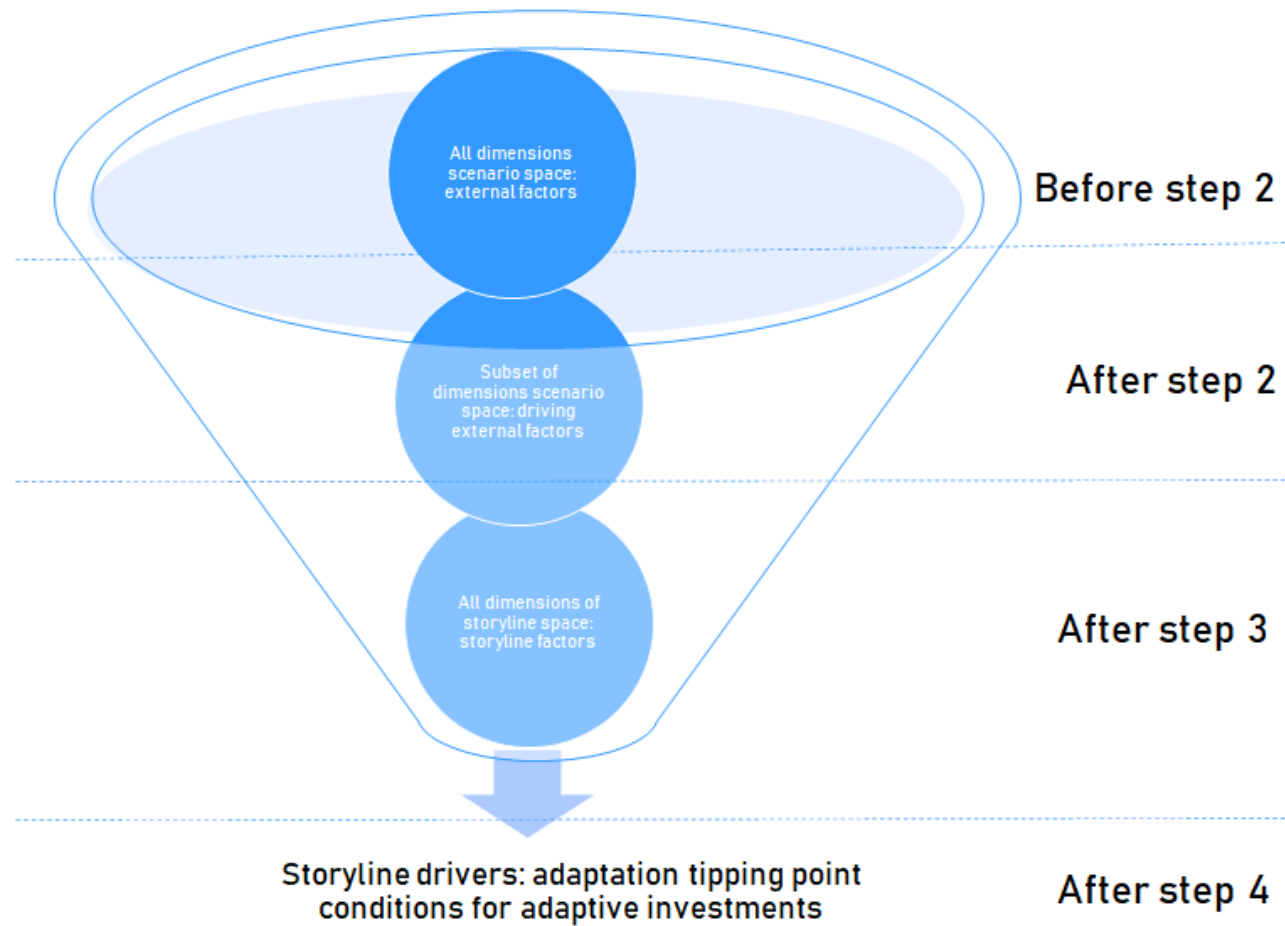


Figure 41: schematic representation of the process for identification of storyline drivers (adaptation tipping point conditions). The indicated steps refer to the steps in figure 40.

7.2.2 Options for robustness improvement for the Medium Voltage network

The investments of the MIEK investment path for the 380 kV-, 150 kV-, H₂-, HTLH-, ODO- and NODO-networks comprised fixed investment packages for several reference years. In contrast, the investments in the MV-network were defined via an investment rule. This rule was based on the rated capacity of connected customer sites to an infrastructure node and a threshold value thereof¹³. The stress test of the MIEK investment path resulted in investment patterns over time for investments in the MV-network (see figure 42).

The investment rule led to a good short-term (100% of facilitated scenarios) and long-term robustness performance (98% of facilitated scenarios) on capacity for the Medium Voltage network. This good performance is feasible in case the maximum investment peak for the network appears not too high. Therefore, it was investigated whether this maximum investment peak appeared to be problematic and what measures could be taken to flatten this peak. A detailed report-out of the analysis have been shared within the project. In this report, only the conclusions of this study are described.

Examination of figure 42 led to the conclusion that the highest observed investment peak arose in 2030. Expert examination led to the conclusion that this investment peak seemed not to lead to feasibility problems. However, it is interesting to understand whether robust investments could be diagnosed that were necessary across the reference years in all scenarios. Upfront investments would lead to no regret investments while reducing the potential maximum investment peak. Analyses showed that two specific investments at a certain location were required in every scenario that was simulated. These no regret investments could be planned in 2025 in order to reduce the potential investment peak in 2030. Figure 43 shows the resulting downward shift in investment peak.

Next to the identification of the robust investments, PRIM-analyses have been conducted for the understanding of the drivers of the investment peak in 2030. It appeared that the technology transition towards E-boilers and E-furnaces in 2030 combined with onshore solar PV and onshore wind growth were drivers for the shown investment peak in 2030.

The analysis of the Medium Voltage network showed that it was possible to diagnose no regret investments that can lead to flattening of the maximum investment peak. As already stated earlier, validation (and improvement) of the multi-model tool and the scenario space is a logical next step in order to enable more reliable and trustworthy simulation results that are good enough to inform the real decision-making process on the strategic direction for a robust, adaptive investment path.

¹³ Details on the applied investment rule are confidential. Details of the analysis have been reported separately.

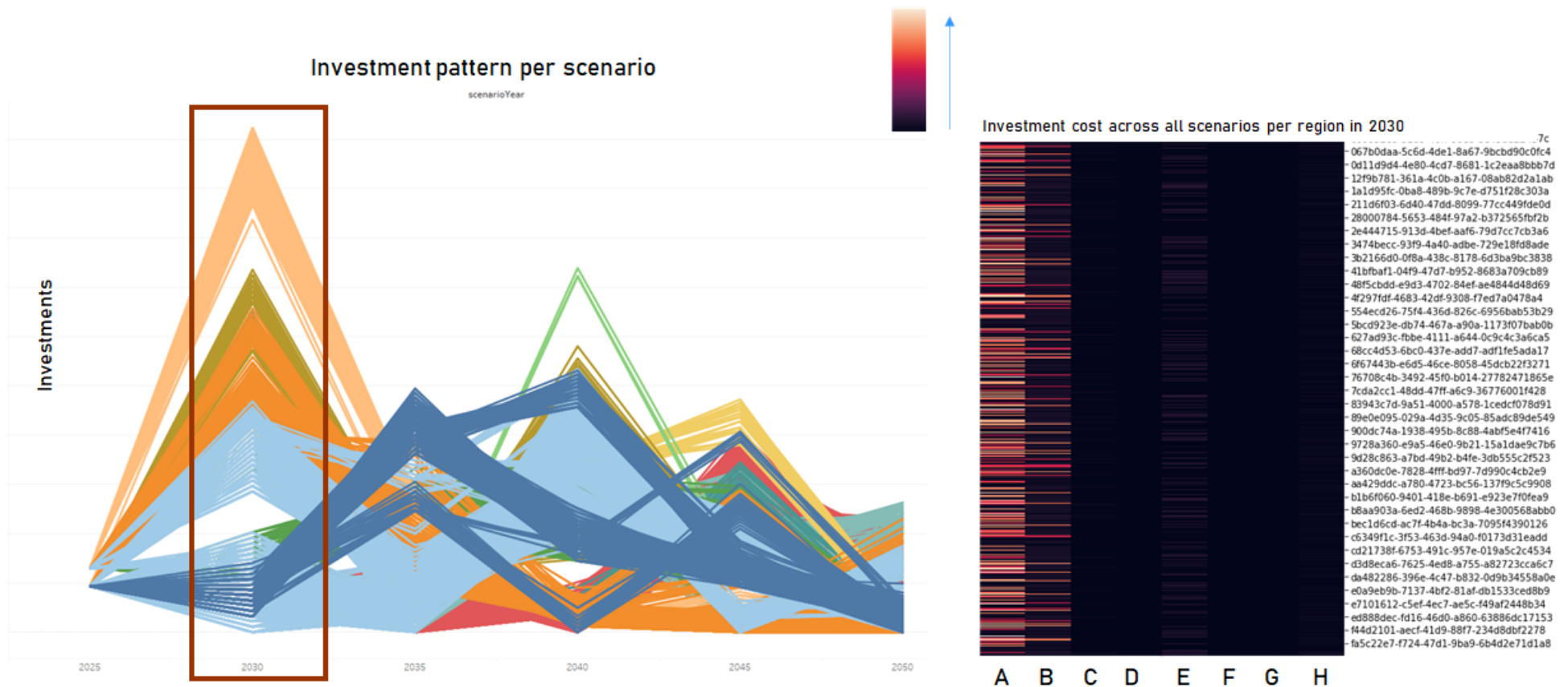


Figure 42: investment patterns over time in the MV-network in 9,980 scenarios (left). Medium Voltage investments allocation per location in 2030 (right). The y-axis represents different scenarios. At the x-axis different geographical locations for MV-infrastructure elements are shown. The magnitude of investment per scenario per location is indicated with a color scale.



Figure 43: illustration of the impact of the addition of robust investments in 2025: a reduction of the potential investment peak in 2030.

8. Discussion

In this section the project results are discussed. It is assessed to what extent the research goals have been successfully met. Furthermore, an assessment is made on what is needed to implement the Gridmaster method for decision support in real decision-making processes for long-term investment planning of integrated investment planning in the Netherlands.

The discussion is structured as follows. First, the potential of the developed Gridmaster method to support strategic decision-making processes on long-term investment planning of integrated energy infrastructure is discussed. Subsequently, the specific insights for the HIC Rotterdam is elaborated on. Hereafter, participatory modeling is addressed. Finally, the relevant aspects for decision-making on how to proceed with the further development of the Gridmaster method and associated tooling is discussed.

8.1 Potential of developed Gridmaster method for decision support on strategic decision-making for integrated energy infrastructure in the context of deep uncertainty of the energy system evolution

The following research questions at the start of the project relate to the development of the Gridmaster method.

- How can the current practice of long-term investment planning for energy infrastructure be expanded and adapted to better inform the decision-making process on societally desirable evolutions of the energy system with information about the impact of energy infrastructure?
- How can the current practice of long-term investment planning for energy infrastructure be expanded and adapted to develop a strategic direction for a robust, adaptive investment plan for integrated energy infrastructure within the context of deep uncertainty of the energy transition?

From these research questions, it follows that the developed Gridmaster method should be capable to:

1. Inform the decision-making process on societally desirable evolutions of the energy system with information about the impact of energy infrastructure in various options for the long-term evolution of the energy system.
2. Create a strategic direction for a robust, adaptive investment plan for integrated energy infrastructure that is capable to effectively deal with the deep uncertainty of the evolution of the energy system.

Below, it is discussed to what extent the demanded capabilities have been incorporated in the developed Gridmaster method.

8.1.1 Capability to indicate the impact of infrastructure for options of long-term energy system evolution pathways

A designed scenario space that encompasses scenarios for energy system evolution over time is a central feature of the developed Gridmaster method. The advantage of a scenario space, in contrast to the current practice of using three or four scenario (cornerstone) points, is that there are no theoretical limits for the number of scenarios that can be included in this space. For example, the scenario space developed in the case study encompassed 10^{19} scenarios. This feature removes a barrier for stakeholder engagement in the creation of scenarios that might impact the energy infrastructure. Instead of a necessary replacement or adjustment of

a scenario, in case the number of scenarios is limited to three or four, other scenarios can simply be added to the scenario space. Furthermore, compared to the limited number of scenarios in the current practice, the scenario space is better capable to reflect the real deep uncertainty that grid operators are confronted with for long-term investment planning.

Although the scenario space enhances stakeholder engagement and allows a broader vision on potential energy system evolution scenarios, it also has a potential downside. The vast amount of possible scenarios makes it hard or impossible to meaningfully compare the impact of energy infrastructure in these scenarios for decision-making on socially desirable energy system evolutions. The three or four scenario (cornerstone) points, used in the current practice, has the advantage that it is relatively easy to understand the different impacts of energy infrastructure in these scenarios. In the Gridmaster method, the problem of too many scenarios for a sensible comparison of options for energy system evolutions, is dealt with by the creation of storylines of energy system evolution. These storylines, encompass the main drivers for the evolution of transport capacity demand over time for the considered energy infrastructure. These main drivers, are not determined a priori, but a posteriori. By so-called PRIM-analyses the most impactful dimensions of the scenario space are revealed. This is a way to separate important scenario developments from less important ones from an energy infrastructure investment planning standpoint. As a consequence, instead of a vast number of possible scenarios, a limited number of storylines arises that encompass the most important driving forces for the growth of transport capacity evolution over time for the considered energy infrastructure. In the case study, for the 380 kV- and H₂-network, 360 storylines were created from a scenario space encompassing 10¹⁹ scenarios. These 360 storylines were built from five independent storyline factors. A specific combination of values for these parameters yields a single storyline. All possible combinations of values for these parameters lead to 360 storylines. This structure enables a structured dialogue about potential energy system evolution pathways. By coupling of the storylines to the overload evolution for the energy infrastructure, it is possible to indicate the magnitude of overload development for a specific storyline. Since the magnitude of overload relates to the social costs (investment cost and spatial impact) of energy infrastructure, in this way, information about the impact of energy infrastructure per storyline can be given. For interpretability purposes, a system of overload classes has been developed with limited categories (six). The impact of a specific network for a storyline is indicated by the resulting maximum overload class over the planning horizon for the storyline.

In the project insufficient attention has been given to the interaction with decision-makers on how this structured information can support them in decision-making processes on the selection of socially desirable long-term energy system evolution pathways. Another point of attention is the plausibility of the scenarios that describe the possible energy system evolution in a specific geographic area. These scenarios should also be plausible on a higher scale level. For example, the scenario developments in the HIC Rotterdam should be plausible in relation to plausible scenarios for the energy system evolution in the Netherlands. Validation of the plausibility of scenarios within the scenario space in relation to the higher scale level energy system might result in the necessity to change the initial set up of the scenario space. In the case study HIC Rotterdam, this validation has not been conducted within the project team. The following research question summarizes this point of attention: how is uniform sampling of the scenario space ensured if a not uniform part of the selected scenarios is regarded as invalid after the plausibility check at the higher energy system scale level?

The developed method looks promising in providing impact of energy infrastructure information in the decision-making process on long-term socially desirable energy system evolution pathways. However, next to gaining experience with the method, further development of the method, associated digital tooling and data input is necessary for use in real decision-making on long-term energy system goals. It is recommended to

further develop the method and tooling in a real decision-making contexts to accelerate the practical value for real life decision-making. Areas of further improvement are:

- Tailoring of decision support information to the needs of decision-makers and the further transfer of the method from theory to practice.
- Further assessment of the definition of overload classes and the relation to investment cost and spatial impact of energy infrastructure.
- Further assessment of the definition of the method for the computation of overload magnitudes for networks (in the case study different methods have been used for the electricity and gas networks).
- Improvements of the scenario space design, and the interaction with stakeholders to include their visions on energy system development into this scenario space.
- Validation of the scenario space for a specific geographic area with the scenario space for the energy system at a higher scale level (e.g. scenario space of HIC Rotterdam in relation to the scenario space for the Netherlands).
- Validation and improvement of the multi-model simulation tool in order to create more reliable overload results.

8.1.2 Capability to create a strategic direction for a robust, adaptive investment plan for integrated energy infrastructure

For the creation of a strategic direction for a robust, adaptive investment plan for integrated energy infrastructure, the following information is needed:

1. Information, given a candidate investment path for energy infrastructure, about the possible evolution of the range of overload magnitudes over time for the considered energy networks as a consequence of the deep uncertainty of the energy system evolution.
2. Information, given a candidate investment path for energy infrastructure, about the short-term robustness performance on capacity for energy networks.
3. Information, given a candidate investment path for energy infrastructure, about the short-term overload magnitude of infrastructure elements across many scenarios. This information reveals those energy infrastructure elements for which robust investments should be considered.
4. Information, given a candidate investment path for energy infrastructure, about the relevant dimensions in potential energy system evolution pathways that significantly impact the long-term growth towards specific overload magnitudes for the considered energy networks. These dimensions and the relevant ranges per dimension are summarized in a storyline space for the energy system evolution.
5. Information, given a candidate investment path for energy infrastructure, about the storyline drivers. These storyline drivers are the dominant conditions in the energy system evolution that, in the long run, will lead to specific overload magnitudes. Storyline drivers correspond to adaptation trigger conditions for which coupled adaptive investments should be designed. In case the evolution of the energy system is heading into the direction of the adaptation trigger conditions, the corresponding adaptive investments should be planned for a timely realization of sufficient transport capacity for the facilitation of the energy system evolution.

6. Information, given a candidate investment path for energy infrastructure, about the overload of infrastructure elements for a storyline driver that in the long run will lead to unacceptable overload magnitudes with the current investment path. This information provides insights into effective options for adaptive investments that should be linked to storyline drivers (adaptation trigger conditions).
7. Information about path dependencies of potential future developments of the energy system. This information leads to the understanding of the evolution of the deep uncertainty of the energy system evolution. This enables the creation of a monitoring system that timely signals the necessity for a re-assessment of the current investment path.
8. A measurement system (metrics) for the determination of the robustness performance of an investment path.

Based on this information, the requirements can be formulated for an effective method for the creation of a strategic direction for a robust, adaptive investment plan for energy infrastructure. An other requirement for an effective method is that the execution of the method can be carried out within a reasonable lead time.

Table 21 shows an assessment of the extent to which the developed Gridmaster method can successfully meet the formulated requirements. From this assessment, it can be concluded that the developed Gridmaster method seems promising as a way to create a strategic direction for a robust, adaptive investment path for integrated energy infrastructure. Eight out of nine requirements are met by the Gridmaster method. It is questionable whether the requirement on an acceptable lead time for the execution of the method will be met. It is certain that, due to the innovative nature of the Gridmaster method, further application and standardization of the Gridmaster method and associated digital tooling will lead to reduced lead times for data handling and analyses. Moreover, large scale computation can be expanded to allow for > 10,000 simulations in a short timeframe (couple of weeks). As described above, next steps should be taken in the development and execution of the Gridmaster method to enable added value to real decision-making on long-term investment choices for integrated energy infrastructure.

Table 21: assessment of the capability of the developed Gridmaster method for the development of a strategic direction for a robust, adaptive investment plan for integrated energy infrastructure

Requirement	Assessment of Gridmaster method
1. Providing a range of overload magnitudes over time for energy networks based on a representation of the 'real' deep uncertainty of the energy system evolution	<p>- Gridmaster method meets this requirement:</p> <ul style="list-style-type: none"> • In the case study the 'real uncertainty' was represented by 9,980 scenarios uniformly sampled from the developed scenario space. In case a better representation of the 'real uncertainty' is required, the number of selected scenarios from the scenario space can be increased. • For 9,980 scenarios the overload evolution over the planning horizon was calculated for all considered networks that were part of the energy infrastructure. A logical evolution of the connection of sites to the network nodes of the energy networks was part of the model, leading to a logical energy system configuration during the simulations for scenarios. For example, the model can cope with the re-use of a former methane pipeline for H₂ transport. Furthermore, electricity connections of sites switch to other voltage levels in case certain threshold values for electricity connection capacities are exceeded.
2. Providing insight into the short-term robustness performance of the investment path	<p>- Gridmaster method meets this requirement:</p> <ul style="list-style-type: none"> • A metric for the determination of the short-term robustness performance has been defined and applied in the case study.
3. Providing insight into the short-term overload magnitude of energy infrastructure elements in many scenarios	<p>- Gridmaster method meets this requirement:</p> <ul style="list-style-type: none"> • Via the developed overload classification system, the overload magnitude in various reference years across 9,980 scenarios was calculated in the case study. 'DNA-map' visualization capability leads to insight into the short-term overload magnitude across many scenarios for each infrastructure element. • In the case study, robust investments have been identified for the MV-network.

Requirement	Assessment of Gridmaster method
4.Capability to create a relevant storyline space that encompasses the dominant dimensions of the energy system evolution and its relevant ranges relevant for long-term investment planning of integrated energy infrastructure ¹⁴	<p>- Gridmaster method meets this requirement:</p> <ul style="list-style-type: none"> • Application of PRIM-analyses in the case study, which is part of the developed method, were effective in the creation of storylines for the 380 kV- and H₂-network. PRIM-analysis as a way to find storylines-overload relations looks promising.
5.Capability to identify storyline drivers (adaptation trigger conditions)	<p>- Gridmaster method meets this requirement:</p> <ul style="list-style-type: none"> • 11 storyline drivers (with sufficient statistical significance) have been found for the 380 kV- and H₂-network by the execution of PRIM-analysis on the storyline-overload data. These storyline drivers are the adaptation trigger conditions for which specific adaptive investment packages should be designed.
6. Providing insight into the overload magnitude of energy infrastructure elements for storyline drivers	<p>- Gridmaster method meets this requirement:</p> <ul style="list-style-type: none"> • For the case study, the developed visualization tool shows overload data per infrastructure element for specific storylines via a 'DNA-map'. Via an additional functionality, not present in the developed visualization tool, it is possible to create such a 'DNA-map' for the conditions of a storyline driver.

¹⁴ In the case study, drivers for location specific overload magnitude developments for energy infrastructure elements of the 380 kV- and H₂-networks were not targeted. In future work, investigation into these drivers might also be relevant.

Requirement	Assessment of Gridmaster method
7. Incorporating path dependency functionality of future energy system evolution pathways in the scenario space	<p>- Gridmaster method meets this requirement:</p> <ul style="list-style-type: none"> • Several potential path dependencies for the energy system evolution have been taken into account in the developed scenario space in the case study: <ul style="list-style-type: none"> ○ Dependency of the evolution of spatial free area for the integration of new conversion technology assets in the HIC Rotterdam: <ul style="list-style-type: none"> ▪ Implementation of CCS leads to a longer existence of certain oil refineries, leading to less spatial area for new technologies integration (leading thus to a path dependency in the evolution of the energy system), ▪ Growth of DAC technology, a technology with a huge spatial footprint, limits the available free area for new technologies integration (leading thus to a path dependency in the evolution of the energy system), ▪ Early closure of current plants, create early spatial area availability for the integration of new technologies (leading to path dependency). ○ Various technology pathways for the replacement of the current fossil methane fired utility production assets have been defined, representing technology change pathways. • For future work, it should be evaluated whether the applied modeling practice for path dependency in the case study could be improved to simplify the analysis into path dependency relations with overload magnitude developments.
8. Use of adequate metrics for the robustness performance measurement of an investment path	<p>- Gridmaster method meets this requirement:</p> <ul style="list-style-type: none"> • A first set of robustness metrics have been defined for the robustness performance measurement of an investment path. Also ideas for expansion of this set of metrics have been generated in the project.
9. Acceptable lead time for the execution of the method	<p>- Gridmaster method might meet this requirement:</p> <ul style="list-style-type: none"> • Lead time for simulation of 9,980 scenarios required ca. 1.5 weeks. • Data collection, data handling, data analysis and visualization of results required significant time. Also the development of the method required a substantial amount of time. However, during the case study a lot has been learned on data handling, data analysis and visualization of results. Furthermore, a limited group of professionals was involved in these activities. Therefore, it is expected that continued application and development of the Gridmaster method and associated tools will reduce lead times for the execution of Gridmaster projects.

8.2 Decision-relevant information about the long-term development of integrated energy infrastructure for HIC Rotterdam

The following research question, formulated at the start of the project, relates to the request for relevant practical insights for the long-term development of integrated energy infrastructure for HIC Rotterdam:

- What is the robustness of the developed MIEK investment path for HIC Rotterdam and what decision relevant information can support the decision-making on the long-term system objective the grid operators should aim for to facilitate with integrated energy infrastructure?

In the project, the MIEK investment path was stress tested. The robustness performance on capacity (short-term and long-term) of the MIEK investment path has been calculated. Furthermore, storyline-overload relations were determined for the 380 kV- and H₂-networks that can be used to inform the decision-making process on socially desirable long-term evolutions of the energy system with information about the impact of energy infrastructure.

For the 380 kV-network an overload magnitude of overload class 4 was identified that should be mitigated by robust, no regret investments on the short-term. Furthermore, for the 380 kV- and H₂-networks 11 storyline drivers have been identified. These storyline drivers are adaptation tipping point conditions that will, in case no adaptive investments are planned, lead to a specific overload magnitude for either the 380 kV- or H₂-network on the long run. In addition, for the MV-network, robust, no regret investments have been diagnosed that can reduce the maximum potential investment peak for MV-network investments.

Although the computed overload values showed logical relations with scenario events, it appeared that the quality of the overload computation for some networks was too inaccurate to draw quantitative conclusions¹⁵. Moreover, the developed scenario space was not properly validated in relation to the scenario space for bigger scale energy system that it is part of (the energy system of the Netherlands). However, the quality of overload computations was good enough for the testing of process steps of the developed Gridmaster method.

The overload computation for the 380 kV- and 150 kV-network turned out to be too inaccurate. This can have multiple causes:

- A computational error in the modelling chain from scenario space up to and including the load flow calculation.
- A methodological problem in the computation of overload values for the electricity networks from overload values of the individual network elements.
- (An) implausible relation(s) within the scenario space that leads to implausible electricity flows across the electricity networks in several scenarios.

Also some modeling anomalies have been observed in the overload calculation for the HTLH-network.

¹⁵ The kind of models used, will not lead to very accurate investment magnitudes. However, the set up of the models will lead, after proper validation of the models, to sufficient detail for the determination of a strategic direction for a robust, adaptive investment path. After determination of this strategic direction, the used load flow models in the current practice of grid planning need to be used for an exact assessment of required investments in energy infrastructure.

A rigorous validation of the modelling tool (for all networks) and scenario space is necessary to ensure a sufficient accuracy of the calculated overload values for infrastructure elements and corresponding networks. Based on this validation, it becomes clear which of the obtained decision-relevant information about the long-term development of integrated energy infrastructure for HIC Rotterdam can be reused for informing the real decision-making processes.

8.3 Participatory modeling

A key feature of the new Gridmaster method is that it incorporates ‘participatory modeling’, by allowing all relevant stakeholders to take part in the modelling exercise itself, or to contribute to the development of the to be considered relevant scenario space. For example as part of this project, all members of the consortium – each having its own background and expertise – contributed to the development of the simulation multi-model tool and/or relevant assumptions. This is vital since long-term modeling of the possible energy system evolution requires expertise and views from a wide range of knowledge areas, such as energy infrastructure planning, load flow calculations, potential energy system evolutions, data management, large scale computing and data analysis. Given that no single organization possesses all the required knowledge and expertise, another advantage of participatory modeling is that it facilitates learning and knowledge transfer among the involved stakeholders on investment planning for energy infrastructure, which ultimately should pave the way for achieving broader social consensus for the resulting decisions. The cooperation between the participating consortium organizations in the case study, is experienced as supportive in the creation of a comprehensive scenario space and coherent multi-model energy system evolution model.

In addition, cooperation between various organizations supported problem solving in the design and realization of the multi-model tool. For future work in the field of ‘Gridmaster’, the practice of participatory modeling seems useful.

8.4 Considerations for decision-making on continuation of Gridmaster development

The project showed that the developed Gridmaster method seems promising for decision support on long-term investment planning of integrated energy infrastructure. However, the developed method was not completely tested in the case study. Furthermore, associated digital tooling, data handling methods, data analysis methods and participative practices should be further improved to develop the Gridmaster method into a decision support practice that is used to inform real decision-making processes on long-term investment planning of integrated energy infrastructure. In short, an effort is needed to implement the Gridmaster method in real decision-making processes on long-term investment planning of integrated energy infrastructure.

For a fast development and implementation of the method, standardization of the method and digital tooling is required. Standards for scenario space and coherent energy system models can be made for 1) an industrial cluster; 2) a city, 3) a rural region, 4) a province and 5) the Dutch main infrastructure. After development, these standards can be rolled out across the Netherlands. After the development of the first ‘standards’ it is less time consuming to further improve these standards in the course of time. Thus, the biggest investment is needed for the creation of the first standards.

After the investment cost for the creation of standards, exploitation cost will arise during the execution of the Gridmaster method in different geographical areas. Furthermore, an effort is needed for the implementation of the Gridmaster method in the grid operator organizations.

Below the costs aspects and benefits of an upgrading of the Gridmaster method towards a new practice for decision support are summarized. This information is aimed to facilitate decision-making on how to proceed with the Gridmaster initiative after the project: is it desirable to upgrade the Gridmaster method or not? And if desirable, what is a desired development path?

Benefits of Gridmaster upgrade towards implementation for decision support in real decision-making on long-term investment planning of integrated energy infrastructure.

Approximately 104 billion Euro of investments in energy infrastructure (methane, H₂ and electricity) are expected to be necessary in the time period from now till 2050 to support the energy transition in the Netherlands [24, 31]. The deep uncertainty about the energy system poses huge challenges in making the right investment decisions on capacity expansion and re-use of existing energy infrastructure. Wrong investment decisions can lead to:

- Blocking of socially desirable energy system evolution pathways by transport capacity limitations.
- Stranded assets of energy infrastructure.

The Gridmaster method is promising in dealing with this deep uncertainty. Upgrade of the Gridmaster method will probably lead to better investment choices leading to the following benefits:

- 1) The ability to facilitate a wide range of energy system evolution scenarios, lowering the risk of blocking of socially desirable energy system evolution pathways.
- 2) The ability to timely plan new adaptive investments in case the energy system evolution is heading into a direction that requires additional transport capacity. In case the energy system evolution direction does not lead to increased transport capacity requirements, no adaptive investments are necessary. The capability to identify adaptive investments will prevent unacceptable stranded assets while the risk of blocking of socially desirable energy system evolution pathways is reduced.
- 3) Better alignment of investment plans for the different energy networks due to the fact that coordination of investment plans for different energy networks is part of the Gridmaster method.
- 4) More societal support for investment choices of grid operators due to the encouragement of stakeholder engagement in the decision-making process, the capability to include stakeholder visions in the scenario space and the enhanced transparency of how decisions are made.

Costs aspects for the implementation and execution of the Gridmaster method

- Investment costs for the creation of standards for 1) an industrial cluster, 2) a city, 3) a rural region, 4) a province and 5) the Dutch national main infrastructure.
- Exploitation cost for the execution of Gridmaster studies in different geographical areas.
- Effort (cost) for the integration of the Gridmaster processes into the grid operator organizations.

9. Conclusions

The following conclusions can be drawn about the developed Gridmaster method and practical decision support information related to the long-term planning of integrated energy infrastructure for HIC Rotterdam.

- Although the developed method can be further improved on most aspects, the method looks promising in:
 - providing information on the impact of energy infrastructure in the decision-making process on long-term evolution pathways of a socially desirable energy system.
 - creating a strategic direction for a robust, adaptive investment path for integrated energy infrastructure.
- Most requirements for a method that is able to create a strategic direction for a robust, adaptive investment path of integrated energy infrastructure are met by the developed Gridmaster method. Only some doubt exists whether the application of the Gridmaster method for a specific energy system scope can be done within an acceptable timeframe. In the executed project, the analysis steps demanded more time than expected. Not all steps of the Gridmaster method could be tested in the project. However, it is relevant to note that, given the innovative character of the Gridmaster method, a significant learning potential is still present for improvement of the efficiency of the execution of such projects. Also, it should be noted that a small team was responsible for the execution of the analyses. Organizational scale up and built-up of knowledge, will accelerate the execution of analyses.
- Participatory modeling, in which various organizations cooperate in the development and building of energy system modeling tools, appears an effective means for the development of the Gridmaster method. Among others, it increased the quality and authority of the developed multi-model simulation model.
- The developed Gridmaster method is not completely tested in the case study. Furthermore, associated digital tooling, data handling methods, data analysis methods and participative practices should be further improved to develop the Gridmaster method into a decision support practice that is used to inform real decision-making processes on long-term investment planning of integrated energy infrastructure.
- Large-scale simulations for stress testing of an investment path, in which the overload evolution over time of the energy infrastructure is explored in many scenarios (~10,000) can be done in a relatively short timeframe (~1.5 weeks) for the modelled geographic scope (HIC Rotterdam) using the developed multi-model toolset. It is possible to scale up the computational capacity in case more simulations would need to be executed in future Gridmaster projects.
- The conceptual set-up of the developed scenario space forms a good starting point for the development of scenario spaces for similar studies in other geographic areas and/or other energy subsystems. A point of attention for future work is the execution of a plausibility check with the scenario space at the higher scale level in order to improve the number of plausible scenarios encompassed in the designed scenario space.
- In the developed scenario space, several potential path dependencies for the energy system evolution have been successfully modeled. Path dependency is important to consider for planning of energy-infrastructure under deep uncertainty.

- A stakeholder dialogue together with organizations that potentially impact the future transport capacity requirements for energy infrastructure adds value in the development of the scenario space and coherent energy system multi-model.
- The developed overload classification method is suitable for the indication of the impact of energy infrastructure in different options for long-term energy system evolution. However, this method should be further refined to enable the coupling of overload classes to societal costs for energy infrastructure. These societal costs for energy infrastructure comprise two components: 1) the order of magnitude of investment costs and 2) the spatial impact of energy infrastructure expansion.
- The set of developed robustness metrics seems sufficiently adequate for a first assessment of the robustness of an investment path for integrated energy infrastructure, *i.e.* the measurement of the performance of an investment path across many transient scenarios.
- The calculated robustness performances on capacity for the MIEK investment path for HIC Rotterdam confirms the added value of coordination of long-term investment planning for the individual energy networks.
- The designed multi-model simulation tool is capable of calculating overload values for infrastructure elements of the various networks, considered in the HIC Rotterdam case study, on a hourly basis for six reference years during the planning horizon. The nature of the multi-model enabled an assessment of the integrated energy infrastructure across many scenarios.
- A logical evolution of the connection of sites (parts of the energy system) to the network nodes of the energy networks is successfully incorporated into the multi-model, leading to a logical energy system configuration during the simulations for scenarios. For example, the model can cope with the re-use of a former methane pipeline for H₂-transport. Furthermore, electricity connections of sites switch to other voltage levels in case certain threshold values for electricity connection capacities are exceeded.
- The confidence in an acceptable accuracy of overload computations for some networks (especially the 380 kV and 150 kV-networks) is insufficient to enable robust quantitative conclusions to be drawn about the robustness of the MIEK investment path for the HIC Rotterdam case study. However, the computed overload values in the HIC Rotterdam case study seem consistent with scenario events, and thus sufficient for the purposes of testing of the developed Gridmaster method for these networks.
- Stress testing of the MIEK investment path with ~ 10,000 scenarios yields overload ranges over time for the considered energy networks. This information indicates the possible overload magnitude on the short-term that should be mitigated with robust, no regret investments in order to facilitate a wide range of scenarios with the integrated energy infrastructure. Compared to the current investment planning practice, the Gridmaster method provides more insight into the possible range of overload on the short-term, due to the increased number of scenarios used for the overload exploration over time.
- ‘Storylines’ – which describe the dominant dimensions of the scenario space that determine the transport capacity evolution over time for the considered energy infrastructure – can help in simplifying the

sensemaking process and interpreting results across many thousands of simulations. PRIM analysis, in combination with the structure of the scenario space, seems a promising approach to finding storyline–overload relations.

- For the 380 kV- and H₂-network in total 11 storyline drivers have been identified. These storyline drivers are the adaptation tipping point conditions for which specific adaptive investment packages should be designed. In case the energy system evolution progresses into the direction of adaptation tipping point conditions, the linked adaptive investment package should be planned (the linking of adaptive investment packages to storyline drivers has not been executed in the project). It should be noted that it is impossible, with the current investment planning practice, to identify these 11 storyline drivers as scenario points. Upfront determination of storyline drivers without modelling, that is part of the current practice, is not achievable given the vast amount of plausible scenarios and unknown impact of these scenarios on the overload conditions of the considered energy infrastructure. Especially, since several of these storyline drivers consist of combined developments of different external factors.
- The analysis of the Medium Voltage network shows that it is possible to diagnose robust, no regret investments that can lead to the reduction of the maximum potential investment peak. This decision support information has been used in a real investment decision case for this network.
- The developed visualization tool is a good starting point for the communication of results obtained from the application of the Gridmaster method to experts.
- The 'DNA'-map visualizations, incorporated into the developed visualization tool, seem effective in creating insight into overload conditions of energy infrastructure elements and energy networks across sets of scenarios or storyline drivers. It is straightforward to apply 'DNA-map' visualizations for storyline drivers in order to support the identification of adaptive investments (this functionality was not built into the visualization tool in the project).

10.Recommendations

In decision-making on the follow-up of the Gridmaster HIC Rotterdam project, a trade-off must be made between the advantages of a Gridmaster method implementation as a decision support practice and the associated costs for the realization of this implementation. Part of these costs include 'investment costs' for the creation of 'Gridmaster standards' for 1) an industrial cluster, 2) a city, 3) a rural region, 4) a province and 5) the Dutch main energy infrastructure. A 'Gridmaster standard' provides a good basis for a 'Gridmaster assessment' for a typical energy system, supporting the acceleration of the Gridmaster method as a decision support practice. Furthermore, the expected exploitation costs and costs for the integration of Gridmaster processes into grid operator organizations need to be considered.

Table 22 highlights the identified areas for improvement of the Gridmaster method, associated digital tooling and analyses practices. For each identified issue, a recommendation is given to resolve this issue. This table can be used for the scoping of next Gridmaster projects.

Table 22: recommendations for future improvements

Gridmaster step	Identified issue/weakness	Recommendations for future improvements
1. General	Insufficient awareness at decision-makers about the societal impact in case the deep uncertainty of the energy system evolution is insufficiently addressed in long-term investment planning of integrated energy infrastructure	<ul style="list-style-type: none"> - Start an awareness project for top management of grid operator and government organizations about the societal risks in case the deep uncertainty of the long-term energy system evolution is insufficiently addressed in long-term investment planning for integrated energy infrastructure. - Create an accessible narrative to explain the impact of insufficiently addressing the deep uncertainty on energy system evolution in long-term investment planning of integrated energy infrastructure. - Create an accessible narrative to explain how application of the Gridmaster method leads to a robust, adaptive investment path that reduces societal risks and increases the societal opportunities for a socially desirable energy system evolution. - Intensify interactions with decision-makers in future Gridmaster projects.
	Insufficient awareness at grid strategists / grid operator experts how the Gridmaster method can support the development of a strategic direction for a robust, adaptive investment plan of integrated energy infrastructure.	<ul style="list-style-type: none"> - Start a dialogue with grid strategists / strategy experts at grid operators about decision-support for long-term investment planning and the potential of the Gridmaster method to support the creation of a strategic direction for a robust, adaptive investment plan for integrated energy infrastructure. - Intensify interactions with grid strategists / strategy experts in future Gridmaster projects.
	The absence of a standard / basis set up of a 'Gridmaster' practice for long term integrated investment planning of energy infrastructure at typical energy systems. This absence impedes implementation of the Gridmaster method for real decision-making.	<ul style="list-style-type: none"> - Develop standards for 1) an industrial cluster, 2) a city, 3) a rural area, 4) a province and 5) the Dutch national main energy infrastructure.

Gridmaster step	Identified issue/weakness	Recommendations for future improvements
1. General	Missed opportunity to increase the policy coordination scope for steering towards a socially desirable energy system evolution.	<ul style="list-style-type: none"> - Include land use policies in the scope of a future use case. For example, the land use policies of harbor companies affect the potential structural change at industrial sites of an industrial cluster, thereby influencing the potential pathways for energy system evolution. - Include policies for steering private investments in the scope of a future use case. For example, policies that stimulate rooftop PV-systems in the built environment or battery investments in particular areas in a city, affect the energy system evolution and thereby the energy transport demand evolution over time.
	Too little involvement of the academia	<ul style="list-style-type: none"> - Actively involve the academic community for the acceleration of the development of methods, processes, and tools that improve the quality of decision-support practices for decision-making on long-term investment planning of energy infrastructure. Find an organizational solution to align use cases with the long-term PhD-project lead times.
2. Develop scenario space and coherent energy system multi-model	Insufficient incorporation of flexibility options into the scenario space and coherent energy system multi-model	<ul style="list-style-type: none"> - Better include flexibility options, such as energy storage options and demand side management into the scenario space and coherent multi-model simulation tool.

Gridmaster step	Identified issue/weakness	Recommendations for future improvements
2. Develop scenario space and coherent energy system multi-model	Not commonly executed plausibility check of the scenario space with the scenario space at the higher system level	<ul style="list-style-type: none"> - Perform a plausibility check of the developed scenario space at the higher scale energy system level. - Answer the following research question: how can uniform sampling of the scenario space ensured if a not uniform part of the selected scenarios is regarded as invalid after the plausibility check at the higher energy system scale level?
	Overload calculations for some networks not of sufficient quality	<ul style="list-style-type: none"> - Intensify interactions between 'Gridmaster-experts' and grid experts to improve the quality of overload computation (especially for 380 kV- and 150 kV-networks) - Perform a more rigorous validation of calculation modules, e.g. testing with historical data, before launching simulations. - Evaluate the method for robustness metric computation on capacity for the electricity networks - Further validate the load flow modules for methane- and H₂-networks.
	Relatively big analysis effort to assess the impact of modeled path dependency relations on overload evolutions over time	<ul style="list-style-type: none"> - Evaluate whether the applied modeling practice for path dependency in the case study could be improved to simplify the analysis into path dependency relations with overload magnitude developments.

Gridmaster step	Identified issue/weakness	Recommendations for future improvements
3. Select socially desirable storylines	Relation between overload class and societal cost (investment cost and spatial impact) of energy infrastructure has not been made	<ul style="list-style-type: none"> - Develop the relation between overload class and societal cost of energy infrastructure. - Refine the initial set up of the overload class system as a measure for the societal cost of energy infrastructure.
	Storyline-overload relations for 360 storylines were shown in the visualization tool. User experience indicated that the presented information was too complicated to be used as decision support information.	<ul style="list-style-type: none"> - Further develop the visualization tooling that supports the communication of the impact of energy infrastructure on options for the long-term energy system evolution. Interact with decision-makers in this development process.
	Not tested process step 2C of the Gridmaster method: social dialogue for determination of socially desirable storylines	<ul style="list-style-type: none"> - Test process step 2C in a use case.
4. Develop strategic direction for robust, adaptive investment path	No experience with trade-off analysis with different options for investment paths due to lack of time in executed projects	<ul style="list-style-type: none"> - Execute process step 'iterative stress testing' (3C – 3F) of the Gridmaster method to create different options for strategic directions for a robust, adaptive investment path. Subsequently, execute the process step 'trade-off analysis' together with decision-makers.

Gridmaster step	Identified issue/weakness	Recommendations for future improvements
4. Develop strategic direction for robust, adaptive investment path	Too complicated analysis results for decision-support information	- Intensify interactions with decision-makers in future Gridmaster projects.
	Not tested process step 3A: Selection of scenarios for candidate investment path selection	- Test process step 3A in a use case
	Not tested process step 3B: Selection of promising candidate investment paths	- Test process step 3B in a use case
	Not tested process step 3C: Selection of scenarios for stress testing	- Test process step 3C in a use case
	Not tested process step 3F: Improve investment path: add robust and adaptive investments	- Test process step 3F in a use case
	Not tested process step 3G: Trade-off decision-making on the strategic direction for a robust, adaptive, integrated investment path	- Test process step 3G in a use case
5. Monitor development of energy system	Not tested process step 4: Monitoring of energy system development for adaptation	- Test process step 4 in a use case

Gridmaster step	Identified issue/weakness	Recommendations for future improvements
6. Data analyses	- Insufficient reliable results of the applied time-series clustering algorithm	- Investigate the effectivity of other / adjusted simulation data analyses, like the examination of the effectivity of other time series clustering algorithms as a part of PRIM-analyses.
	- Drivers for location specific overload magnitude developments have not been investigated seriously.	- Investigate drivers for location specific overload magnitude developments for energy infrastructure elements
7. Visualization-tool	- Incompleteness of the visualization tool functionality to create decision-support information	<ul style="list-style-type: none"> - Further develop effective visualizations to inform decision-makers with decision support information - Interact with decision-makers in the further development of the visualization tooling

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Appendix A: evolution of the project focus

In the course of the project one of the original research questions was replaced and project objectives have been adjusted accordingly (see tables A1 and A2). Instead of a more global execution of the developed Gridmaster process steps, it was decided to focus more on a detailed analysis of the stress test results of the MIEK investment path. As a consequence, not all designed process steps of the Gridmaster method have been tested in the case study HIC Rotterdam.

Table A1: original versus final research questions

Research question	Original project plan	Actually executed project
1. How can the current practice of strategic investment planning for energy infrastructure be expanded and adapted to develop robust investment plans for integrated energy infrastructure within the context of deep uncertainty of the energy transition?	Yes	Yes
2. What is a robust, adaptive investment plan for integrated energy infrastructure for the HIC Rotterdam that supports investment decision-making of individual organizations?	Yes	No
3. What is the robustness of the developed MIEK investment path for HIC Rotterdam and what decision relevant information can support the decision-making on the long-term system objective the grid operators should aim for to facilitate with integrated energy infrastructure?	No	Yes

Table A2: original versus final objectives of the project

Objective	Original project plan	Actually executed project
1. Development of a new method for strategic adaptive grid planning for integrated energy infrastructure	Yes	Yes
2. Development of a scenario space for long-term investment planning of integrated energy infrastructure in HIC Rotterdam	Yes	Yes
3. Development of a multi-model simulation tool that enables a better understanding of the performance of integrated investment plans	Yes	Yes
4. Gaining insight into robust investment plans for integrated energy infrastructure in HIC Rotterdam	Yes	No
5. Development of interactive visualizations of promising adaptive investment paths for integrated energy infrastructure in HIC Rotterdam via Adaptation Pathways Maps	Yes	No
6. Public dissemination of the developed method and (software)tools	Yes	Yes
7. Active dissemination of developed knowledge and insights with relevant stakeholders	Yes	Yes
8. Execution of a stakeholder dialogue with relevant industry organizations to align the design of the scenario space	No	Yes
9. Development of interactive visualizations of the impact of scenario storylines on overload patterns during the planning horizon for the H ₂ - and 380 kV-networks with the following added value: 1) Provision of decision support information for a stakeholder dialogue on the long-term ambition of the energy system evolution 2) A tool that can be used for the design process for the creation of a strategic direction for a robust, adaptive investment path of integrated energy infrastructure	No	Yes

Appendix B: scenario space details

More documentation about the developed scenario space can be found at <https://github.com/GridMaster2022>.

Appendix C: motivation for choices on subsystem division of the HIC Rotterdam energy system

Subsystem	Sites part of subsystem	Motivation for the definition of the subsystem
1. Oil based and non-oil based hydrocarbon production and (repowered) coal fired power plants	<ul style="list-style-type: none"> • Current oil refinery sites • Current central SMR sites (H₂ production for supply to oil refineries) • Current coal fired power plant sites • Maasvlakte 2 area that is allocated for non-oil based hydrocarbon production plants 	<ul style="list-style-type: none"> • Oil refineries are part of the same global value chain. • In case CCS is rolled out in HIC Rotterdam, probably Shell and Exxon refineries will be connected to this system. • In case the H-vision project is rolled out, BP and Shell refineries and potentially Exxon refinery will be connected to the central ATR production unit (blue H₂ production asset). • In case the H-vision project is rolled out, probably the current coal fired plants will be partly fed with blue H₂ ex the central ATR production unit. • Assumption that firms that exploit oil refineries are also willing to exploit non-oil based hydrocarbon production plants.
2. Chlorine based chemical cluster, other industrial sites and (repowered) methane based utility production sites	<ul style="list-style-type: none"> • Current chlorine based chemical cluster • Current industrial sites that are not part of the chlorine based chemical cluster and are no oil refinery • Current central methane fired power plant sites and central methane fired cogeneration plant sites 	<ul style="list-style-type: none"> • The interdependency of chlorine demanding sites on the availability of affordable chlorine produced by the central chlorine production site. • The currently fossil methane based utility production assets that provide steam and HT heat for the considered industrial processes. Assumed is that technology change in utility production will affect all industrial sites that are part of this subsystem. • Structural change of currently central gas fired power plants and cogeneration plants is likely related to the structural change of utility production technologies that are currently based on fossil methane.

Subsystem	Sites part of subsystem	Motivation for the definition of the subsystem
3. Nuclear power plant	<ul style="list-style-type: none"> Envisioned site at Maasvlakte 2 	<ul style="list-style-type: none"> Nowadays, no nuclear power plant is part of the energy system of the HIC Rotterdam. However, future political decision-making might lead to the integration of a nuclear power plant at Maasvlakte 2. The political choice for the integration of a nuclear power plant is considered to be independent on the political decision-making on the growth of other power production assets that impact the energy system of the HIC.
4. Onshore wind	<ul style="list-style-type: none"> Various sites across the HIC Rotterdam 	<ul style="list-style-type: none"> The political choice for the growth onshore wind capacity is considered to be independent on the political decision-making on the growth of other power production assets that impact the energy system of the HIC.
5. Onshore solar PV	<ul style="list-style-type: none"> Various sites across the HIC Rotterdam 	<ul style="list-style-type: none"> The political choice for the growth onshore solar PV capacity is considered to be independent on the political decision-making on the growth of other power production assets that impact the energy system of the HIC.
6. Offshore wind import	<ul style="list-style-type: none"> Assumed is that the installed wind land capacity is connected to a specific 380 kV station 	<ul style="list-style-type: none"> The political choice for the growth offshore wind land capacity is considered to be independent on the political decision-making on the growth of other power production assets that impact the energy system of the HIC.
7. Built environment	<ul style="list-style-type: none"> Current Peakshaver Current demand of fossil methane for the built environment that is supplied via the methane backbone that runs across the HIC Rotterdam 	<ul style="list-style-type: none"> The heat supply to the built environment will change from the currently mainly fossil methane based systems to other systems. The built environment is currently affecting the methane infrastructure in the HIC via both the peak shaver and the 'normal' methane supply to the built environment. The peak shaver unit is an emergency methane supply system that only is activated in case of (very) cold periods in which the methane demand for low temperature is extremely high.

Subsystem	Sites part of subsystem	Motivation for the definition of the subsystem
8. Electrical charging of ships & shorepower	<ul style="list-style-type: none"> (Potential) sites for the electrical charging of ships and / or electrical supply during a ships stay at the quay. 	<ul style="list-style-type: none"> During the planning horizon, electrification of shipping will be one of the trends that will change current shipping. The future development of charging of batteries to drive ships and the power supply during stay at the quay will be independent of other potential change in the other considered subsystems.
9. H ₂ demand hinterland	<ul style="list-style-type: none"> Site located at the east side of the HIC Rotterdam 	<ul style="list-style-type: none"> H₂ demand hinterland represents the H₂ demand of systems that could be supplied by H₂ via the HIC. H₂ supply will either be imported via the seaside and or produced in the HIC Rotterdam via water electrolysis plants. H₂ demand systems that are supplied via the HIC Rotterdam might consist of H₂ demand for non-oil based hydrocarbon production in other industrial clusters inside or outside the Netherland, H₂ demand for the built environment and H₂ demand for mobility.
10. Dutch electricity market	<ul style="list-style-type: none"> Sites that encompass conversion assets that react on the electricity market dynamics (electricity price signal). 	<ul style="list-style-type: none"> Conversion assets that produce or demand electricity, located in the HIC Rotterdam, are part of the Dutch electricity market system. The operation of a gas fired electricity generation asset is for example driven by the electricity market conditions. Furthermore, the electricity exchange between the HIC Rotterdam and its surroundings is dependent on the electricity market situation. Due to the impact of the Dutch electricity market on the operations of part of the conversion assets that are located in the HIC Rotterdam, the Dutch electricity market is chosen as a subsystem of the HIC energy system.

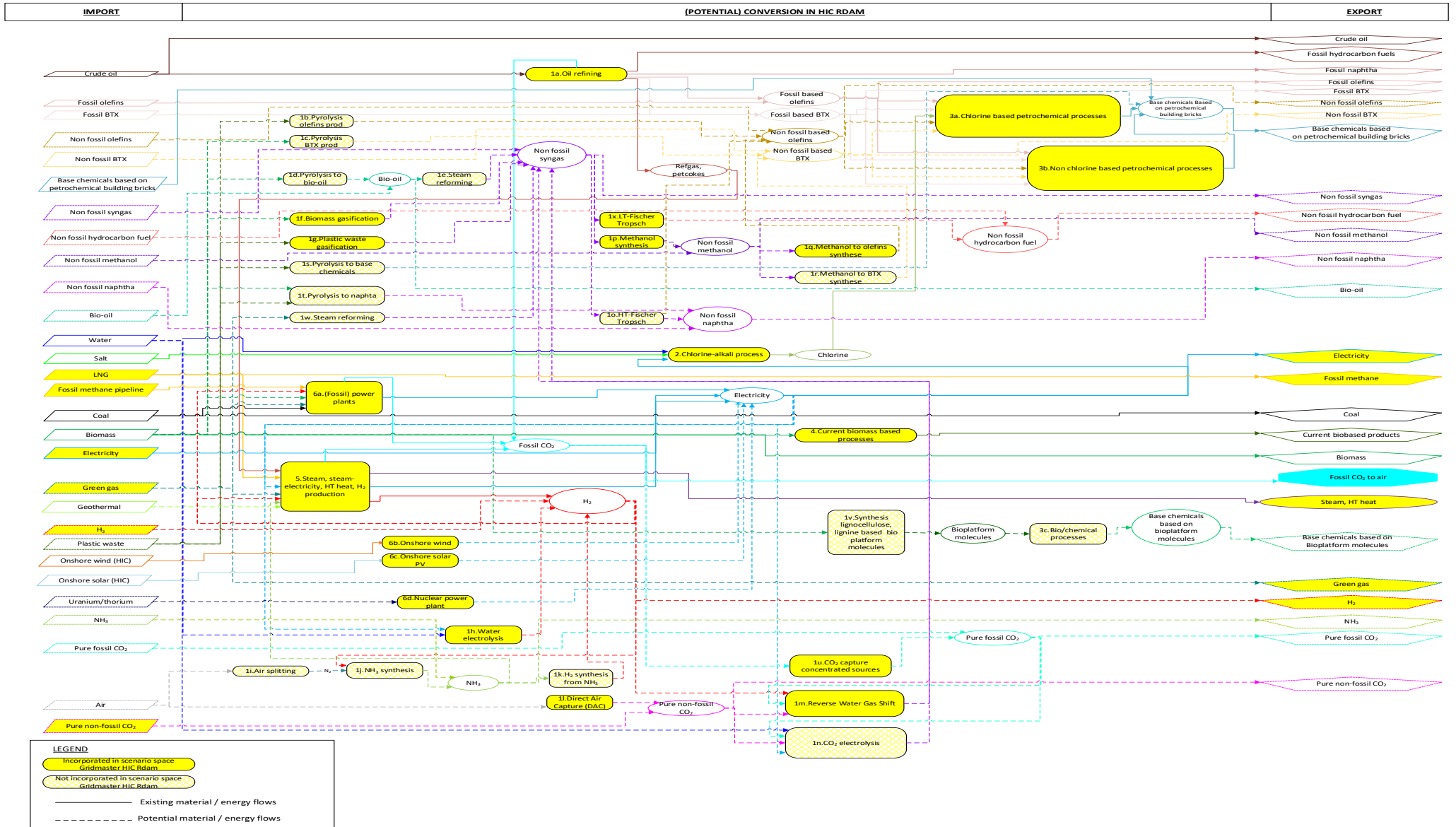
Appendix D: current situation of the HIC Rotterdam energy system

More documentation about the developed scenario space can be found at <https://github.com/GridMaster2022>.

Appendix E: super structure of (potential) energy system of the HIC Rotterdam

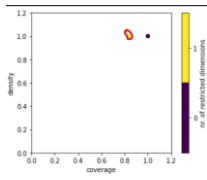
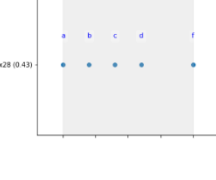
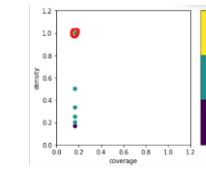
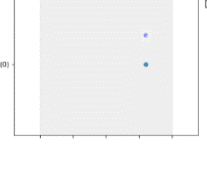
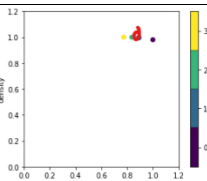
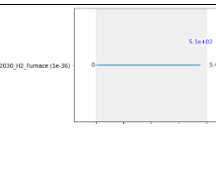
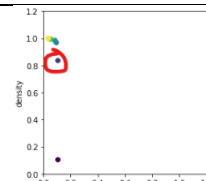
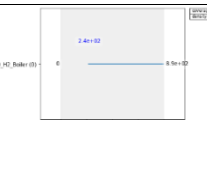
See the scheme on the next page.

(Potential) building bricks for the scenario space for investment planning of integrated energy infrastructure for HIC Rotterdam



Appendix F: Results of PRIM-analyses for identification of drivers for specific overload patterns for 380 kV-, H₂-, ODO- and NODO-networks

Hydrogen PRIM-analysis with overload classes

Year	Class	Box 1		Box 2		Comments and PRIM
2025	1	<pre>coverage density id mass mean res_dim 0 1.00000 0.9999 0 1.00000 0.9999 0 0.33356 1.0000 1 0.33360 1.0000 1</pre> 	<pre>coverage density id mass mean res_dim 0 0.33356 1.0000 1 0.33360 1.0000 1 res_dim 1 Name: 1, dtype: object</pre> <pre>box 1 min max qp values x28 [0.0, 0.0, 0.0] [0.0, 0.0, 0.0]</pre> 	<pre>coverage density id mass mean res_dim 0 0.166434 0.166417 0 1.00000 0.166417 0 1 0.166434 0.199760 1 0.833084 0.199760 1 2 0.166434 0.249738 2 0.666367 0.249738 1 3 0.166434 0.333000 3 0.499750 0.333000 1 4 0.166434 0.499550 4 0.333134 0.499550 1 5 0.166434 0.999400 5 0.166517 0.999400 1 6 0.139660 1.000000 6 0.129646 1.000000 2</pre> 	<pre>coverage density id mass mean res_dim 0 0.166434 0.166417 0 1.00000 0.166417 0 1 0.166434 0.199760 1 0.833084 0.199760 1 2 0.166434 0.249738 2 0.666367 0.249738 1 3 0.166434 0.333000 3 0.499750 0.333000 1 4 0.166434 0.499550 4 0.333134 0.499550 1 5 0.166434 0.999400 5 0.166517 0.999400 1 6 0.139660 1.000000 6 0.129646 1.000000 2</pre> <pre>box 5 min max qp values x28 [0.0, 0.0, 0.0] [0.0, 0.0, 0.0]</pre> 	<p>Cases: 10010</p> <p>Total coverage box 1+ 2 = 0.16+0.83=0.99</p>
2030	1	<pre>coverage density id mass mean res_dim 0 1.00000 0.999912 0 1.00000 0.999912 0 0.093541 0.999912 1 0.879732 0.999912 1 2 0.806760 0.996804 2 0.875137 0.996804 1 3 0.806593 0.999757 3 0.806497 0.999757 2 4 0.779941 1.000000 4 0.769862 1.000000 2</pre> 	<pre>coverage density id mass mean res_dim 0 0.806593 0.999757 3 0.806497 0.999757 2 4 0.779941 1.000000 4 0.769862 1.000000 2</pre> <pre>box 1 min max qp values 2030_H2_Furnace [0.0, 0.0, 0.0] [0.0, 0.0, 0.0]</pre> 	<pre>coverage density id mass mean res_dim 0 0.106459 0.104385 0 1.00000 0.104385 0 1 0.106459 0.836000 1 0.124863 0.836000 1 2 0.094540 0.968685 2 0.095695 0.968685 2 3 0.087918 0.978458 3 0.088103 0.978458 3 4 0.084250 0.984524 4 0.083908 0.984524 3 5 0.052465 0.994208 5 0.051743 0.994208 4 6 0.040240 0.997475 6 0.039556 0.997475 5 7 0.034841 1.000000 7 0.034162 1.000000 6</pre> 	<pre>coverage density id mass mean res_dim 0 0.106459 0.104385 0 1.00000 0.104385 0 1 0.106459 0.836000 1 0.124863 0.836000 1 2 0.094540 0.968685 2 0.095695 0.968685 2 3 0.087918 0.978458 3 0.088103 0.978458 3 4 0.084250 0.984524 4 0.083908 0.984524 3 5 0.052465 0.994208 5 0.051743 0.994208 4 6 0.040240 0.997475 6 0.039556 0.997475 5 7 0.034841 1.000000 7 0.034162 1.000000 6</pre> <pre>box 1 min max qp values 2030_H2_Bolter [0.0, 0.0, 0.0] [0.0, 0.0, 0.0]</pre> 	<p>Cases: 9816</p> <p>Total coverage box 1 + 2 = 0.89+0.1=0.99</p>

2		<div><div><div><div><div>coverage</div><div>density</div><div>id</div><div>mass</div><div>mean</div><div>res_dim</div></div><div><div>0</div><div>1.000000</div><div>0.019479</div><div>0</div><div>1.000000</div><div>0.019479</div><div>0</div></div><div><div>1</div><div>0.054410</div><div>0.133660</div><div>1</div><div>0.124863</div><div>0.133660</div><div>1</div></div><div><div>2</div><div>0.054410</div><div>0.185960</div><div>2</div><div>0.080701</div><div>0.185960</div><div>2</div></div><div><div>3</div><div>0.054410</div><div>0.573918</div><div>3</div><div>0.029168</div><div>0.573918</div><div>2</div></div><div><div>4</div><div>0.030769</div><div>0.611321</div><div>4</div><div>0.026471</div><div>0.611321</div><div>3</div></div><div><div>5</div><div>0.533333</div><div>0.981132</div><div>5</div><div>0.010568</div><div>0.981132</div><div>3</div></div></div><div><div>box 5</div><div><div>min</div><div>max</div><div>qp values</div></div><div><div>2035_ElectrolyzerChlorine</div><div>0.0</div><div>182.5</div><div>[-1.0, 2.435748208190814e-24]</div></div><div><div>2035_H2_Bolier</div><div>341.5</div><div>893.0</div><div>[5.17364514812387e-87, -1.0]</div></div><div><div>2035_demandInterLand</div><div>4000.0</div><div>5000.0</div><div>[1.2740217225891e-55, -1.0]</div></div></div></div><div><div><div><div>density</div><div>0.0</div><div>0.2</div><div>0.6</div><div>0.8</div><div>1.0</div><div>1.2</div></div><div><div>coverage</div><div>0.0</div><div>0.2</div><div>0.4</div><div>0.6</div><div>0.8</div><div>1.0</div><div>1.2</div></div></div><div><div>0</div><div>1</div><div>2</div><div>3</div></div><div><div>nr of restricted dimensions</div><div>0</div><div>1</div><div>2</div><div>3</div></div></div><div><div>2035_demandInterLand (5.0e+03)</div><div>2e+03</div><div>4e+03</div><div>5e+03</div></div><div><div>2035_H2_Bolier (5.2e+01)</div><div>0</div><div>2.0e+02</div><div>3.0e+02</div><div>4.0e+02</div></div><div><div>2035_ElectrolyzerChlorine (5.0e+00)</div><div>0</div><div>1.0e+02</div><div>2.0e+02</div><div>3.0e+02</div></div></div>		Cases: 195
2035	1	<div><div><div><div><div>coverage</div><div>density</div><div>id</div><div>mass</div><div>mean</div><div>res_dim</div></div><div><div>0</div><div>1.000000</div><div>0.193385</div><div>0</div><div>1.000000</div><div>0.193385</div><div>0</div></div><div><div>1</div><div>1.000000</div><div>0.260626</div><div>1</div><div>0.749675</div><div>0.260626</div><div>1</div></div><div><div>2</div><div>1.000000</div><div>0.390963</div><div>2</div><div>0.499750</div><div>0.390963</div><div>1</div></div><div><div>3</div><div>1.000000</div><div>0.702150</div><div>3</div><div>0.252632</div><div>0.702150</div><div>1</div></div><div><div>4</div><div>0.994880</div><div>0.832335</div><div>4</div><div>0.233543</div><div>0.832335</div><div>2</div></div><div><div>5</div><div>0.962610</div><div>0.863766</div><div>5</div><div>0.221756</div><div>0.863766</div><div>3</div></div><div><div>6</div><div>0.963656</div><div>0.941441</div><div>6</div><div>0.199500</div><div>0.941441</div><div>3</div></div><div><div>7</div><div>0.938319</div><div>0.946407</div><div>7</div><div>0.189800</div><div>0.946407</div><div>3</div></div><div><div>8</div><div>0.905479</div><div>0.994085</div><div>8</div><div>0.177904</div><div>0.994085</div><div>3</div></div><div><div>9</div><div>0.892716</div><div>0.996407</div><div>9</div><div>0.168017</div><div>0.996407</div><div>3</div></div><div><div>10</div><div>0.804752</div><div>0.998096</div><div>10</div><div>0.157427</div><div>0.998096</div><div>3</div></div><div><div>11</div><div>0.752046</div><div>0.999321</div><div>11</div><div>0.147038</div><div>0.999321</div><div>4</div></div><div><div>12</div><div>0.646459</div><div>1.000000</div><div>12</div><div>0.132173</div><div>1.000000</div><div>4</div></div></div><div><div>box 4</div><div><div>min</div><div>max</div><div>qp values</div></div><div><div>2035_demandInterLand</div><div>4000.0</div><div>5000.0</div><div>[-1.0, 0.0]</div></div><div><div>2035_Electrolyzer</div><div>0.0</div><div>4307.5</div><div>[-1.0, 4.81488372779524e-18]</div></div></div></div><div><div><div><div>coverage</div><div>density</div><div>id</div><div>mass</div><div>mean</div><div>res_dim</div></div><div><div>0</div><div>1.000000</div><div>0.193385</div><div>0</div><div>1.000000</div><div>0.193385</div><div>0</div></div><div><div>1</div><div>1.000000</div><div>0.260626</div><div>1</div><div>0.749675</div><div>0.260626</div><div>1</div></div><div><div>2</div><div>1.000000</div><div>0.390963</div><div>2</div><div>0.499750</div><div>0.390963</div><div>1</div></div><div><div>3</div><div>1.000000</div><div>0.702150</div><div>3</div><div>0.252632</div><div>0.702150</div><div>1</div></div><div><div>4</div><div>0.994880</div><div>0.832335</div><div>4</div><div>0.233543</div><div>0.832335</div><div>2</div></div><div><div>5</div><div>0.962610</div><div>0.863766</div><div>5</div><div>0.221756</div><div>0.863766</div><div>3</div></div><div><div>6</div><div>0.963656</div><div>0.941441</div><div>6</div><div>0.199500</div><div>0.941441</div><div>3</div></div><div><div>7</div><div>0.938319</div><div>0.946407</div><div>7</div><div>0.189800</div><div>0.946407</div><div>3</div></div><div><div>8</div><div>0.905479</div><div>0.994085</div><div>8</div><div>0.177904</div><div>0.994085</div><div>3</div></div><div><div>9</div><div>0.892716</div><div>0.996407</div><div>9</div><div>0.168017</div><div>0.996407</div><div>3</div></div><div><div>10</div><div>0.804752</div><div>0.998096</div><div>10</div><div>0.157427</div><div>0.998096</div><div>3</div></div><div><div>11</div><div>0.752046</div><div>0.999321</div><div>11</div><div>0.147038</div><div>0.999321</div><div>4</div></div><div><div>12</div><div>0.646459</div><div>1.000000</div><div>12</div><div>0.132173</div><div>1.000000</div><div>4</div></div></div><div><div>box 4</div><div><div>min</div><div>max</div><div>qp values</div></div><div><div>2035_demandInterLand</div><div>4000.0</div><div>5000.0</div><div>[-1.0, 0.0]</div></div><div><div>2035_Electrolyzer</div><div>0.0</div><div>4307.5</div><div>[-1.0, 4.81488372779524e-18]</div></div></div></div></div>		Cases: 1956

2	<table><thead><tr><th>coverage</th><th>density</th><th>id</th><th>mass</th><th>mean</th><th>res_dim</th></tr></thead><tbody><tr><td>0</td><td>1.000000</td><td>0.277902</td><td>0</td><td>1.000000</td><td>0.277902</td><td>0</td></tr><tr><td>1</td><td>1.000000</td><td>0.361492</td><td>1</td><td>0.749675</td><td>0.361492</td><td>1</td></tr><tr><td>2</td><td>0.917319</td><td>0.508295</td><td>2</td><td>0.499750</td><td>0.508295</td><td>1</td></tr><tr><td>3</td><td>0.815702</td><td>0.885554</td><td>3</td><td>0.249625</td><td>0.885554</td><td>1</td></tr><tr><td>4</td><td>0.795484</td><td>0.914804</td><td>4</td><td>0.236839</td><td>0.914804</td><td>2</td></tr><tr><td>5</td><td>0.780686</td><td>0.985796</td><td>5</td><td>0.211965</td><td>0.985796</td><td>2</td></tr><tr><td>6</td><td>0.789355</td><td>0.999508</td><td>6</td><td>0.202177</td><td>0.999508</td><td>2</td></tr><tr><td>7</td><td>0.788441</td><td>1.000000</td><td>7</td><td>0.191969</td><td>1.000000</td><td>3</td></tr></tbody></table> <pre>coverage 0.815702 density 0.885554 id 3 mass 0.249625 mean 0.885554 res_dim 1 Name: 3, dtype: object</pre> <p>box 3</p> <table><thead><tr><th></th><th>min</th><th>max</th><th>qp values</th></tr></thead><tbody><tr><td>2035_demandInterLand</td><td>5000.0</td><td>6500.0</td><td>[0.0, 0.0]</td></tr></tbody></table>	coverage	density	id	mass	mean	res_dim	0	1.000000	0.277902	0	1.000000	0.277902	0	1	1.000000	0.361492	1	0.749675	0.361492	1	2	0.917319	0.508295	2	0.499750	0.508295	1	3	0.815702	0.885554	3	0.249625	0.885554	1	4	0.795484	0.914804	4	0.236839	0.914804	2	5	0.780686	0.985796	5	0.211965	0.985796	2	6	0.789355	0.999508	6	0.202177	0.999508	2	7	0.788441	1.000000	7	0.191969	1.000000	3		min	max	qp values	2035_demandInterLand	5000.0	6500.0	[0.0, 0.0]	<pre>coverage 0.815702 density 0.885554 id 3 mass 0.249625 mean 0.885554 res_dim 1 Name: 3, dtype: object</pre> <p>box 3</p> <table><thead><tr><th></th><th>min</th><th>max</th><th>qp values</th></tr></thead><tbody><tr><td>2035_demandInterLand</td><td>5000.0</td><td>6500.0</td><td>[0.0, 0.0]</td></tr></tbody></table>		min	max	qp values	2035_demandInterLand	5000.0	6500.0	[0.0, 0.0]		Cases: 2713
coverage	density	id	mass	mean	res_dim																																																																													
0	1.000000	0.277902	0	1.000000	0.277902	0																																																																												
1	1.000000	0.361492	1	0.749675	0.361492	1																																																																												
2	0.917319	0.508295	2	0.499750	0.508295	1																																																																												
3	0.815702	0.885554	3	0.249625	0.885554	1																																																																												
4	0.795484	0.914804	4	0.236839	0.914804	2																																																																												
5	0.780686	0.985796	5	0.211965	0.985796	2																																																																												
6	0.789355	0.999508	6	0.202177	0.999508	2																																																																												
7	0.788441	1.000000	7	0.191969	1.000000	3																																																																												
	min	max	qp values																																																																															
2035_demandInterLand	5000.0	6500.0	[0.0, 0.0]																																																																															
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3	<table><thead><tr><th>coverage</th><th>density</th><th>id</th><th>mass</th><th>mean</th><th>res_dim</th></tr></thead><tbody><tr><td>0</td><td>1.000000</td><td>0.533913</td><td>0</td><td>1.000000</td><td>0.533913</td><td>0</td></tr><tr><td>1</td><td>0.955314</td><td>0.622902</td><td>1</td><td>0.749675</td><td>0.622902</td><td>1</td></tr><tr><td>2</td><td>0.903119</td><td>0.964814</td><td>2</td><td>0.500250</td><td>0.964814</td><td>1</td></tr><tr><td>3</td><td>0.864546</td><td>0.976749</td><td>3</td><td>0.472580</td><td>0.976749</td><td>2</td></tr><tr><td>4</td><td>0.818709</td><td>0.980257</td><td>4</td><td>0.442313</td><td>0.980257</td><td>2</td></tr><tr><td>5</td><td>0.746679</td><td>0.997902</td><td>5</td><td>0.399960</td><td>0.997902</td><td>2</td></tr><tr><td>6</td><td>0.696971</td><td>1.000000</td><td>6</td><td>0.372091</td><td>1.000000</td><td>0</td></tr></tbody></table> <pre>coverage 0.903119 density 0.964814 id 2 mass 0.500250 mean 0.964814 res_dim 1 Name: 2, dtype: object</pre> <p>box 2</p> <table><thead><tr><th></th><th>min</th><th>max</th><th>qp values</th></tr></thead><tbody><tr><td>2035_demandInterLand</td><td>6500.0</td><td>10000.0</td><td>[0.0, -1.0]</td></tr></tbody></table>	coverage	density	id	mass	mean	res_dim	0	1.000000	0.533913	0	1.000000	0.533913	0	1	0.955314	0.622902	1	0.749675	0.622902	1	2	0.903119	0.964814	2	0.500250	0.964814	1	3	0.864546	0.976749	3	0.472580	0.976749	2	4	0.818709	0.980257	4	0.442313	0.980257	2	5	0.746679	0.997902	5	0.399960	0.997902	2	6	0.696971	1.000000	6	0.372091	1.000000	0		min	max	qp values	2035_demandInterLand	6500.0	10000.0	[0.0, -1.0]	<pre>coverage 0.903119 density 0.964814 id 2 mass 0.500250 mean 0.964814 res_dim 1 Name: 2, dtype: object</pre> <p>box 2</p> <table><thead><tr><th></th><th>min</th><th>max</th><th>qp values</th></tr></thead><tbody><tr><td>2035_demandInterLand</td><td>6500.0</td><td>10000.0</td><td>[0.0, -1.0]</td></tr></tbody></table>		min	max	qp values	2035_demandInterLand	6500.0	10000.0	[0.0, -1.0]		Cases: 5345							
coverage	density	id	mass	mean	res_dim																																																																													
0	1.000000	0.533913	0	1.000000	0.533913	0																																																																												
1	0.955314	0.622902	1	0.749675	0.622902	1																																																																												
2	0.903119	0.964814	2	0.500250	0.964814	1																																																																												
3	0.864546	0.976749	3	0.472580	0.976749	2																																																																												
4	0.818709	0.980257	4	0.442313	0.980257	2																																																																												
5	0.746679	0.997902	5	0.399960	0.997902	2																																																																												
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	min	max	qp values																																																																															
2035_demandInterLand	6500.0	10000.0	[0.0, -1.0]																																																																															

2040	1	<pre> coverage density id mass mean res_dim 0 1.000000 0.161462 0 1.000000 0.161462 0 1 1.000000 0.163371 1 0.749675 0.163371 1 2 1.000000 0.210071 2 0.699750 0.210071 1 3 1.000000 0.420712 3 0.220225 0.420712 1 4 0.999071 0.623013 4 0.327039 0.623013 2 5 0.999071 0.679697 5 0.223854 0.679697 2 6 0.999071 0.705417 6 0.212767 0.705417 2 7 0.999042 0.705996 7 0.203379 0.705996 2 8 0.996769 0.820093 8 0.177709 0.820093 2 9 0.910791 0.626999 9 0.158126 0.626999 3 10 0.806401 0.670789 10 0.120238 0.670789 4 11 0.659367 0.729065 11 0.190487 0.729065 4 12 0.677394 0.742794 12 0.097003 0.742794 4 13 0.650054 0.768070 13 0.091899 0.768070 4 14 0.623606 0.778335 14 0.066005 0.778335 4 15 0.602730 0.797146 15 0.089410 0.797146 4 16 0.573710 0.808704 16 0.074776 0.808704 5 17 0.535179 0.820611 17 0.077021 0.820611 5 18 0.539849 0.834795 18 0.068325 0.834795 5 19 0.466801 0.860068 19 0.020536 0.860068 5 20 0.434903 0.885122 20 0.005042 0.885122 5 21 0.424271 0.908549 21 0.002463 0.908549 5 22 0.466334 0.919807 22 0.047948 0.919807 6 23 0.590335 0.929054 23 0.045150 0.929054 6 24 0.573747 0.948176 24 0.046431 0.948176 6 25 0.520479 0.970438 25 0.040404 0.970438 6 26 0.277375 0.996867 26 0.020308 0.996867 6 27 0.252804 1.000000 27 0.027769 1.000000 6 </pre> <pre> coverage 0.502273 density 0.793346 id 15 mass 0.603163 mean 0.793346 res_dim 4 Name: 15, dtype: object box 15 min max 2040_demandInterLand 5000.0 7000.0 2040_H2 Import 0.0 1570.0 2040_Electrolyzer 0.0 4192.5 x24 [a, c, f, b] [a, c, f, b] qp values 2040_demandInterLand [-1.0, 8.74659471181180e-207] 2040_H2 Import [-1.0, 3.0847275977920657e-499] 2040_Electrolyzer [-1.0, 9.86769265621347e-488] x24 [5.17415882029180e-13, -1.0] </pre>	Cases: 1076
	2	<pre> coverage density id mass mean res_dim 0 1.000000 0.096704 0 1.000000 0.096704 0 1 1.000000 0.129114 1 0.749675 0.129114 1 2 1.000000 0.193884 2 0.699750 0.193884 1 3 0.887513 0.343409 3 0.250125 0.343409 1 4 0.874907 0.569802 4 0.327039 0.569802 2 5 0.857350 0.327817 5 0.223854 0.327817 2 6 0.844373 0.363710 6 0.212767 0.363710 2 7 0.755418 0.614731 7 0.178366 0.614731 3 8 0.656347 0.654936 8 0.173646 0.654936 3 9 0.633943 0.671985 9 0.159957 0.671985 3 10 0.609907 0.620279 10 0.117371 0.620279 3 11 0.654876 0.628113 11 0.070423 0.628113 3 12 0.538101 0.677097 12 0.025144 0.677097 3 13 0.590246 0.711823 13 0.040555 0.711823 4 14 0.520328 0.770751 14 0.022172 0.770751 4 15 0.546807 0.828321 15 0.019179 0.828321 4 16 0.514871 0.896296 16 0.013405 0.896296 4 </pre> <pre> coverage 0.316821 density 0.818215 id 15 mass 0.839319 mean 0.818215 res_dim 4 Name: 15, dtype: object box 15 min max 2040_demandInterLand 5000.0 7000.0 x24 [a, c, f, b] [a, c, f, b] x25 [b, c] [b, c] qp values 2040_demandInterLand [-1.0, 4.57675807389303e-75] x24 [-1.0, 0.0000000000000000e+00] 2040_H2 Import [1.76182777099512e-09, 6.06479142000000e-242] x25 [1.0001500961104253e-05, -1.0] </pre>	Cases: 969
			Comment: relative low density, possible reason: low amount of cases
	3	<pre> coverage density id mass mean res_dim 0 1.000000 0.648402 0 1.000000 0.648402 0 1 1.000000 0.596136 1 0.749675 0.596136 1 2 0.873044 0.781044 2 0.699750 0.781044 1 3 0.843423 0.801915 3 0.603404 0.801915 2 4 0.819404 0.820013 4 0.649610 0.820013 2 5 0.791238 0.820091 5 0.620335 0.820091 2 6 0.749441 0.853396 6 0.530468 0.853396 2 7 0.709462 0.879532 7 0.530306 0.879532 2 8 0.737697 0.940257 8 0.178903 0.940257 2 9 0.626181 0.966005 9 0.150035 0.966005 2 10 0.620718 1.000000 10 0.140709 1.000000 2 </pre> <pre> coverage 0.364641 density 0.888315 id 1 mass 0.888315 mean 0.888315 res_dim 2 Name: 1, dtype: object box 1 min max 2040_H2 Import 0.0 17322.0 [-1.0, 0.000126646681197727] 2040_demandInterLand 7000.0 10000.0 [0.51702565646650e-187, 2.31e-121] </pre>	Cases: 4474
		<pre> coverage density id mass mean res_dim 0 0.157577 0.070423 0 1.000000 0.070423 0 1 0.157577 0.101195 1 0.046036 0.101195 1 2 0.157577 0.134439 2 0.520632 0.134439 2 3 0.156236 0.197513 3 0.320511 0.197513 2 4 0.126956 0.321854 4 0.178164 0.321854 2 5 0.126956 0.401982 5 0.141142 0.401982 2 6 0.126956 0.434251 6 0.130656 0.434251 2 7 0.126956 0.434251 7 0.130656 0.434251 2 8 0.126956 0.502635 8 0.112876 0.502635 2 9 0.126956 0.553067 9 0.102587 0.553067 2 10 0.126956 0.611410 10 0.092798 0.611410 2 11 0.126956 0.648402 11 0.087504 0.648402 2 12 0.126956 0.690998 12 0.082110 0.690998 2 13 0.126956 0.731959 13 0.077515 0.731959 2 14 0.126956 0.774898 14 0.073219 0.774898 2 15 0.109298 0.799020 15 0.061133 0.799020 3 16 0.086500 0.832258 16 0.046440 0.832258 3 17 0.082624 0.841270 17 0.044052 0.841270 4 18 0.079347 0.849282 18 0.041754 0.849282 4 19 0.075771 0.853904 19 0.039656 0.853904 5 20 0.060796 0.869010 20 0.031266 0.869010 6 21 0.058114 0.875421 21 0.029667 0.875421 6 22 0.044032 0.899543 22 0.021876 0.899543 7 23 0.041797 0.907767 23 0.020577 0.907767 8 24 0.039785 0.912821 24 0.019479 0.912821 8 </pre> <pre> coverage 0.100728 density 0.799922 id 15 mass 0.881313 mean 0.799922 res_dim 3 Name: 15, dtype: object box 15 min max 2040_demandInterLand 5000.0 7000.0 2040_H2 Import 4790.0 20492.0 x24 [a, c, c, d, b] [a, c, c, d, b] qp values 2040_demandInterLand [-1.0, 3.3888793839416703e-181] 2040_H2 Import [2.52368665451297e-190, -1.0] x24 [0.00148772548333566e-1, -1.0] </pre>	Total coverage box 1 + 2 = 0.84+0.1=0.10 = 0.94

4

coverage	density	id	mass	mean	res.dims
0	1.000000	0.706473	0	0.000000	0.706473
1	1.000000	0.275609	1	0.748075	0.275609
2	0.976230	0.404153	2	0.500250	0.404153
3	0.771381	0.489185	3	0.563001	0.489185
4	0.478462	0.538022	4	0.532449	0.538022
5	0.476209	0.570502	5	0.572510	0.570502
6	0.475392	0.600806	6	0.561630	0.600806
7	0.471242	0.626204	7	0.555223	0.626204
8	0.461676	0.652907	8	0.545440	0.652907
9	0.451426	0.680050	9	0.533453	0.680050
10	0.444209	0.706405	10	0.526161	0.706405
11	0.561044	0.822304	11	0.509000	0.822304
12	0.309852	0.895536	12	0.637801	0.895536
13	0.296420	0.948817	13	0.686226	0.948817
14	0.278395	0.923077	14	0.626231	0.923077
15	0.260996	0.931804	15	0.625706	0.931804
16	0.228613	0.948799	16	0.645145	0.948799
17	0.212186	0.968613	17	0.650002	0.968613
18	0.202480	0.974037	18	0.645153	0.974037
19	0.194864	0.984809	19	0.652764	0.984809
20	0.184864	0.993789	20	0.652165	0.993789
21	0.148831	0.976721	21	0.630466	0.976721
22	0.119491	1.000000	22	0.630000	1.000000

```

coverage 0.561044
density 0.822304
id 11
mass 0.6000
mean 0.625706
res.dims 5
name: 11, dtype: object

box 11
min max
0.0 0.600000 [1.0, 4.42723253866129e-15]
0.0 0.600000 [1.0, 4.42723253866129e-15]
0.0 0.600000 [1.0, 4.42723253866129e-15]
0.0 0.600000 [1.0, 4.42723253866129e-15]
0.0 0.600000 [1.0, 4.42723253866129e-15]

```

coverage	density	id	mass	mean	res.dims
0	0.157577	0.070423	0	1.000000	0.070423
1	0.157577	0.101395	1	0.694536	0.101395
2	0.157577	0.134439	2	0.523824	0.134439
3	0.156236	0.197513	3	0.353511	0.197513
4	0.126956	0.318564	4	0.178104	0.318564
5	0.126956	0.381464	5	0.148736	0.381464
6	0.126956	0.401982	6	0.141145	0.401982
7	0.126956	0.434251	7	0.130656	0.434251
8	0.126956	0.502655	8	0.112876	0.502655
9	0.126956	0.553067	9	0.102587	0.553067
10	0.126956	0.611410	10	0.097798	0.611410
11	0.126956	0.648402	11	0.087504	0.648402
12	0.126956	0.690998	12	0.082110	0.690998
13	0.126956	0.731959	13	0.077515	0.731959
14	0.126956	0.774988	14	0.073219	0.774988
15	0.109298	0.799020	15	0.061133	0.799020
16	0.066500	0.832258	16	0.046449	0.832258
17	0.062924	0.841270	17	0.044052	0.841270
18	0.079347	0.849282	18	0.041754	0.849282
19	0.075771	0.853904	19	0.039656	0.853904
20	0.060796	0.869010	20	0.031266	0.869010
21	0.058114	0.875421	21	0.029667	0.875421
22	0.044032	0.899543	22	0.021876	0.899543
23	0.041797	0.907767	23	0.020577	0.907767
24	0.039785	0.912821	24	0.019479	0.912821
25	0.034198	0.921687	25	0.016582	0.921687
26	0.026822	0.937500	26	0.012786	0.937500
27	0.025257	0.941667	27	0.011987	0.941667
28	0.024139	0.947368	28	0.011387	0.947368
29	0.024363	0.947626	29	0.011487	0.947626

```

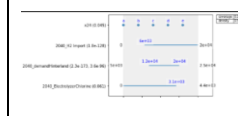
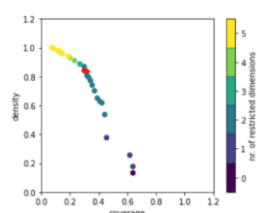
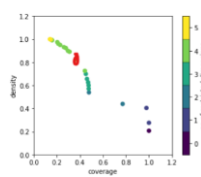
coverage 0.561044
density 0.822304
id 11
mass 0.6000
mean 0.625706
res.dims 5
name: 11, dtype: object

box 11
min max
0.0 0.600000 [1.0, 4.42723253866129e-15]
0.0 0.600000 [1.0, 4.42723253866129e-15]
0.0 0.600000 [1.0, 4.42723253866129e-15]
0.0 0.600000 [1.0, 4.42723253866129e-15]
0.0 0.600000 [1.0, 4.42723253866129e-15]

```

Cases: 2069

Total coverage
box 1 + 2 =
0.36+0.23=0.59



5

coverage	density	id	mass	mean	res.dims
0	1.000000	0.142344	0	1.000000	0.142344
1	1.000000	0.189090	1	0.748075	0.189090
2	1.000000	0.264015	2	0.499999	0.264015
3	1.000000	0.568236	3	0.250225	0.568236
4	0.953758	0.686676	4	0.223354	0.686676
5	0.905889	0.651186	5	0.197882	0.651186
6	0.887640	0.672340	6	0.187793	0.672340
7	0.863764	0.694131	7	0.177005	0.694131
8	0.772402	0.747791	8	0.146058	0.747791
9	0.739237	0.774386	9	0.134112	0.774386
10	0.626404	0.831314	10	0.107782	0.831314
11	0.580758	0.866876	11	0.092596	0.866876
12	0.562107	0.910828	12	0.078414	0.910828
13	0.478230	0.924816	13	0.073619	0.924816
14	0.358889	1.000000	14	0.043952	1.000000

```

coverage 0.626404
density 0.831314
id 10
mass 0.187782
mean 0.107782
res.dims 5
name: 10, dtype: object

box 10
min max
0.0 0.187782 [1.0, 3.38161241526812e-14]
0.0 0.187782 [1.0, 3.38161241526812e-14]
0.0 0.187782 [1.0, 3.38161241526812e-14]
0.0 0.187782 [1.0, 3.38161241526812e-14]
0.0 0.187782 [1.0, 3.38161241526812e-14]

```

coverage	density	id	mass	mean	res.dims
0	0.373596	0.053142	0	1.000000	0.053142
1	0.373596	0.078867	1	0.748075	0.078867
2	0.373596	0.106294	2	0.499999	0.106294
3	0.373596	0.212291	3	0.250225	0.212291
4	0.339888	0.283207	4	0.178712	0.283207
5	0.335399	0.317764	5	0.141145	0.317764
6	0.306180	0.325373	6	0.133853	0.325373
7	0.299157	0.342169	7	0.124363	0.342169
8	0.285112	0.374539	8	0.108281	0.374539
9	0.271770	0.395301	9	0.097792	0.395301
10	0.226124	0.456091	10	0.077822	0.456091
11	0.183889	0.543568	11	0.048147	0.543568
12	0.165730	0.605128	12	0.038957	0.605128
13	0.157903	0.636364	13	0.035161	0.636364
14	0.153090	0.654655	14	0.033263	0.654655
15	0.143365	0.694631	15	0.029767	0.694631
16	0.143961	0.724382	16	0.028269	0.724382
17	0.105317	0.815217	17	0.018380	0.815217
18	0.096910	0.841463	18	0.016382	0.841463
19	0.080056	0.890625	19	0.012786	0.890625
20	0.075140	0.906780	20	0.011787	0.906780
21	0.072331	0.919643	21	0.011188	0.919643
22	0.073034	0.920354	22	0.011288	0.920354

```

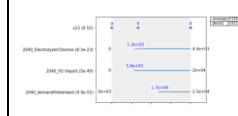
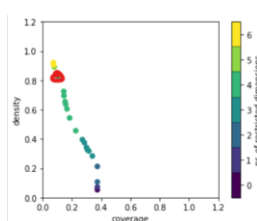
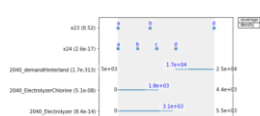
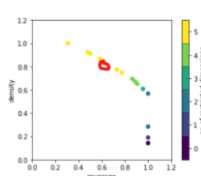
coverage 0.626404
density 0.831314
id 10
mass 0.187782
mean 0.107782
res.dims 5
name: 10, dtype: object

box 10
min max
0.0 0.187782 [1.0, 3.38161241526812e-14]
0.0 0.187782 [1.0, 3.38161241526812e-14]
0.0 0.187782 [1.0, 3.38161241526812e-14]
0.0 0.187782 [1.0, 3.38161241526812e-14]
0.0 0.187782 [1.0, 3.38161241526812e-14]

```

Cases: 1424

Total coverage
box 1 + 2 =
0.36+0.23=0.59

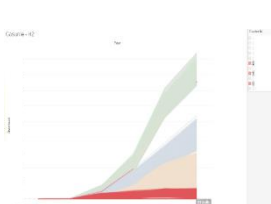
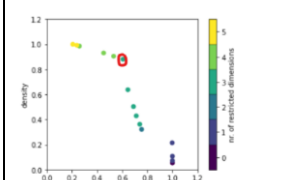
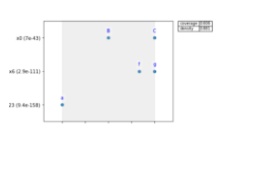
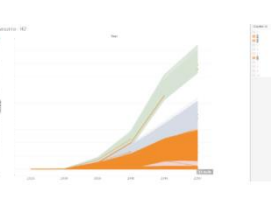
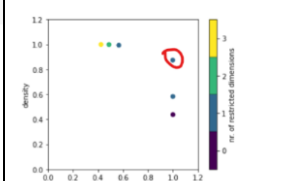
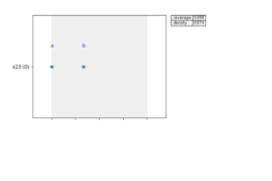
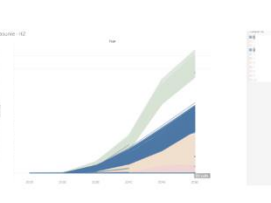
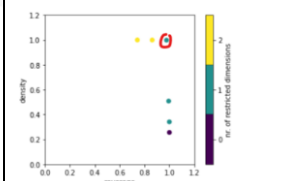
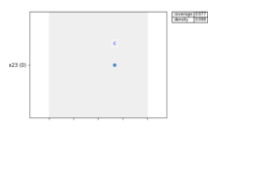


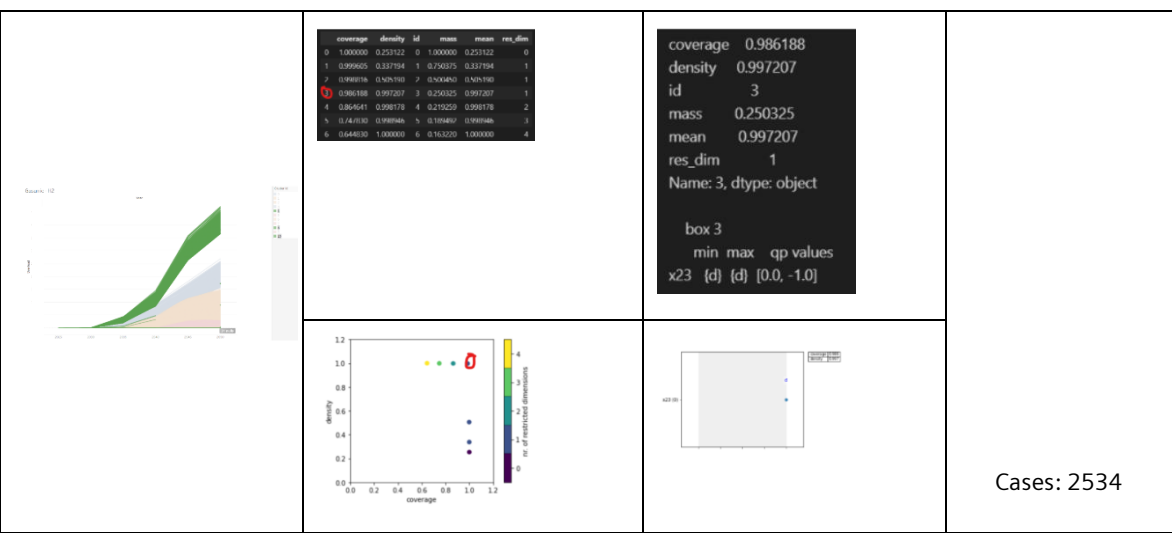
2045	1	<pre>coverage density id mass mean res_dim 0 1.000000 0.032964 0 1.000000 0.032964 0 1 1.000000 0.043971 1 0.749675 0.043971 1 2 1.000000 0.063960 2 0.499750 0.063960 1 3 1.000000 0.111789 3 0.250215 0.111789 1 4 1.000000 0.171345 4 0.187993 0.171345 2 5 1.000000 0.219807 5 0.154937 0.219807 3 6 1.000000 0.261490 6 0.126061 0.261490 3 7 1.000000 0.344883 7 0.090495 0.344883 3 8 1.000000 0.504587 8 0.046328 0.504587 3 9 1.000000 0.532258 9 0.061932 0.532258 4 10 1.000000 0.546272 10 0.058835 0.546272 4 11 1.000000 0.590340 11 0.050839 0.590340 4 12 1.000000 0.662384 12 0.045451 0.662384 4 13 1.000000 0.699452 13 0.047148 0.699452 4 14 0.934364 0.850333 14 0.037960 0.850333 5 15 0.903830 0.894895 15 0.033263 0.894895 5 16 0.866667 0.934641 16 0.020566 0.934641 5 17 0.833334 0.958478 17 0.020868 0.958478 5 18 0.792839 0.972878 18 0.020870 0.972878 5 19 0.718182 0.995152 19 0.023874 0.995152 6 20 0.666006 0.995434 20 0.021876 0.995434 6 21 0.551151 1.000000 21 0.018185 1.000000 7</pre>	<pre>coverage 0.161201 density 0.888891 id 0 mass 0.811263 mean 0.888891 res_dim 0 Name: 11, dtype: object Box 11 min max qp values 2045_demandInterLand 4886.0 18048.0 [-1.0, 1.361118888888889e-16] 2045_H2 Import 0.0 18048.0 [-1.0, 2.5432808815888e-16] 2045_H2 Interceptor 0.0 4887.0 [-1.0, 1.96699880217766e-17] c0 [-1, 1] [-1, 1] [-1, 1] c1 [-1, 1] [-1, 1] [-1, 1] c2 [-1, 1] [-1, 1] [-1, 1] c3 [-1, 1] [-1, 1] [-1, 1] c4 [-1, 1] [-1, 1] [-1, 1] c5 [-1, 1] [-1, 1] [-1, 1] c6 [-1, 1] [-1, 1] [-1, 1] c7 [-1, 1] [-1, 1] [-1, 1] c8 [-1, 1] [-1, 1] [-1, 1] c9 [-1, 1] [-1, 1] [-1, 1] c10 [-1, 1] [-1, 1] [-1, 1] c11 [-1, 1] [-1, 1] [-1, 1] c12 [-1, 1] [-1, 1] [-1, 1] c13 [-1, 1] [-1, 1] [-1, 1] c14 [-1, 1] [-1, 1] [-1, 1] c15 [-1, 1] [-1, 1] [-1, 1] c16 [-1, 1] [-1, 1] [-1, 1] c17 [-1, 1] [-1, 1] [-1, 1] c18 [-1, 1] [-1, 1] [-1, 1] c19 [-1, 1] [-1, 1] [-1, 1] c20 [-1, 1] [-1, 1] [-1, 1] c21 [-1, 1] [-1, 1] [-1, 1]</pre>		Cases: 330	
	2	<pre>coverage density id mass mean res_dim 0 1.000000 0.142463 0 1.000000 0.142463 0 1 1.000000 0.190773 1 0.749675 0.190773 1 2 1.000000 0.261429 2 0.499750 0.261429 1 3 1.000000 0.523088 3 0.250215 0.523088 1 4 1.000000 0.608091 4 0.227279 0.608091 2 5 1.000000 0.632138 5 0.225652 0.632138 2 6 0.988599 0.668802 6 0.214354 0.668802 2 7 0.959495 0.700985 7 0.202777 0.700985 2 8 0.949297 0.743997 8 0.188891 0.743997 2 9 0.943193 0.787802 9 0.180000 0.787802 2 10 0.891457 0.847517 10 0.158005 0.847517 3 11 0.792817 0.949622 11 0.118969 0.949622 3 12 0.754006 0.978841 12 0.112276 0.978841 3 13 0.712624 0.984891 13 0.104483 0.984891 3 14 0.688776 0.993946 14 0.098991 0.993946 3 15 0.648756 0.998647 15 0.091799 0.998647 3 16 0.586835 0.976179 16 0.082908 0.976179 3 17 0.535822 0.998747 17 0.097972 0.998747 3 18 0.445764 1.000000 18 0.080724 1.000000 4</pre>	<pre>coverage 0.161201 density 0.778762 id 0 mass 0.188891 mean 0.778762 res_dim 0 Name: 9, dtype: object Box 9 min max qp values 2045_demandInterLand 4886.0 18048.0 [-1.0, 1.361118888888889e-16] 2045_H2 Import 0.0 18048.0 [-1.0, 2.5432808815888e-16]</pre>		Cases: 1428	
	3	<pre>coverage density id mass mean res_dim 0 1.000000 0.221804 0 1.000000 0.221804 0 1 1.000000 0.292804 1 0.749675 0.292804 1 2 1.000000 0.442804 2 0.499750 0.442804 1 3 0.698334 0.620848 3 0.249625 0.620848 1 4 0.698334 0.633328 4 0.237139 0.633328 2 5 0.697994 0.690883 5 0.228883 0.690883 2 6 0.696433 0.729269 6 0.212064 0.729269 2 7 0.694732 0.764619 7 0.201578 0.764619 2 8 0.692481 0.811609 8 0.188762 0.811609 2 9 0.681675 0.841111 9 0.179802 0.841111 2 10 0.670712 0.866498 10 0.169813 0.866498 2 11 0.655299 0.874762 11 0.161233 0.874762 2 12 0.606385 0.887648 12 0.153033 0.887648 2 13 0.497073 0.938776 13 0.111471 0.938776 3 14 0.470209 0.950864 14 0.108779 0.950864 3 15 0.431046 0.972401 15 0.092897 0.972401 3 16 0.363350 0.988877 16 0.081510 0.988877 3 17 0.301216 0.994806 17 0.067226 0.994806 4 18 0.265457 0.995290 18 0.063630 0.995290 5 19 0.271499 0.996034 19 0.060434 0.996034 5 20 0.252891 0.996074 20 0.058218 0.996074 6 21 0.232326 1.000000 21 0.051543 1.000000 6</pre>	<pre>coverage 0.161201 density 0.811891 id 0 mass 0.811891 mean 0.811891 res_dim 0 Name: 9, dtype: object Box 9 min max qp values 2045_H2 Import 0.0 18048.0 [-1.0, 1.361118888888889e-16] 2045_demandInterLand 4886.0 18048.0 [-1.0, 2.5432808815888e-16]</pre>	<pre>coverage density id mass mean res_dim 0 1.000000 0.068225 0 1.000000 0.068225 0 1 0.307519 0.098231 1 0.694536 0.098231 1 2 0.307519 0.130244 2 0.523824 0.130244 2 3 0.307519 0.192992 3 0.353511 0.192992 2 4 0.301666 0.375771 4 0.178104 0.375771 2 5 0.301666 0.482807 5 0.139347 0.482807 2 6 0.301666 0.547833 6 0.122166 0.547833 2 7 0.301216 0.589926 7 0.111577 0.589926 2 8 0.300215 0.643822 8 0.103486 0.643822 2 9 0.299864 0.702646 9 0.094396 0.702646 2 10 0.299864 0.702646 10 0.094396 0.702646 2 11 0.294912 0.724305 11 0.089182 0.724305 2 12 0.286808 0.783518 12 0.081211 0.783518 2 13 0.284557 0.819715 13 0.077015 0.819715 2 14 0.281855 0.856361 14 0.073020 0.856361 2 15 0.272400 0.887697 15 0.068125 0.887697 2 16 0.252139 0.921053 16 0.060733 0.921053 2 17 0.240432 0.933566 17 0.057137 0.933566 2 18 0.230527 0.942910 18 0.054240 0.942910 2 19 0.219271 0.947471 19 0.051344 0.947471 2 20 0.186853 0.956621 20 0.043352 0.956621 3 21 0.157136 0.966759 21 0.036060 0.966759 4 22 0.176069 0.975610 22 0.028868 0.975610 4 23 0.098604 0.986486 23 0.022176 0.986486 4 24 0.093652 0.990476 24 0.020977 0.990476 5 25 0.055380 1.000000 25 0.012286 1.000000 6</pre>	<pre>coverage 0.161201 density 0.810715 id 13 mass 0.810715 mean 0.810715 res_dim 2 Name: 11, dtype: object Box 11 min max qp values 2045_demandInterLand 4886.0 18048.0 [-1.0, 1.361118888888889e-16] 2045_H2 Import 0.0 18048.0 [-1.0, 2.5432808815888e-16]</pre>	Cases: 2221

						No PRIM box found due to Python error	
	2	<pre>coverage density id mass mean res dim 0 1.00000 0.151713 0 0.00000 0.151713 0 1 1.00000 0.262788 1 0.749675 0.262788 1 2 1.00000 0.303018 2 0.449750 0.303018 1 3 1.00000 0.606279 3 0.750175 0.606279 1 4 1.00000 0.627722 4 0.272526 0.627722 1 5 0.799439 0.673405 5 0.225152 0.673405 2 6 0.594875 0.733010 6 0.205774 0.733010 2 7 0.562225 0.762781 7 0.195385 0.762781 2 8 0.895206 0.841584 8 0.141402 0.841584 3 9 0.792225 0.308812 9 0.728949 0.308812 3 10 0.781405 0.968771 10 0.122266 0.968771 3 11 0.747202 0.578448 11 0.115873 0.578448 3 12 0.718894 0.990826 12 0.110379 0.990826 3 13 0.646861 0.391704 13 0.101788 0.391704 3 14 0.626703 0.997913 14 0.095595 0.997913 4 15 0.567887 0.998881 15 0.089302 0.998881 4 16 0.544817 1.000000 16 0.082029 1.000000 4</pre>	<pre>coverage 0.762225 density 0.762781 id 7 mass 0.195385 mean 0.762781 res_dim 2 Name: 7, dtype: object box 7 min max up values 2050_demandInterLand 4888.0 13000.0 [-1.0, 0.0] 2050_H2 Import 0.0 1.027718 [-1.0, 1.0]</pre>			Cases: 1519	
	3	<pre>coverage density id mass mean res dim 7 1.00000 0.300000 7 0.170100 0.300000 2 8 1.00000 0.412621 8 0.174814 0.412621 2 9 0.995389 0.445719 9 0.132504 0.445719 2 10 0.993658 0.419673 10 0.068402 0.419673 2 11 0.989479 0.517889 11 0.090301 0.517889 2 12 0.978901 0.544996 12 0.090000 0.544996 2 13 0.947946 0.517889 13 0.079513 0.517889 2 14 0.947146 0.504954 14 0.075217 0.504954 2 15 0.949302 0.630363 15 0.079802 0.630363 2 16 0.924990 0.647122 16 0.064007 0.647122 2 17 0.879493 0.702703 17 0.059515 0.702703 2 18 0.862579 0.723979 18 0.064118 0.723979 2 19 0.845466 0.767905 19 0.052442 0.767905 2 20 0.800973 0.796023 20 0.049445 0.796023 2 21 0.818102 0.820760 21 0.044401 0.820760 2 22 0.801268 0.851985 22 0.044401 0.851985 2 23 0.780727 0.834408 23 0.042154 0.834408 2 24 0.747477 0.857491 24 0.039996 0.857491 2 25 0.725559 0.908814 25 0.033809 0.908814 2 26 0.695560 0.921569 26 0.033661 0.921569 2 27 0.558880 0.925452 27 0.026468 0.925452 3 28 0.454971 0.925742 28 0.022414 0.925742 3 29 0.374007 0.994362 29 0.017760 0.994362 4 30 0.328810 1.000000 30 0.015503 1.000000 5</pre>	<pre>coverage 0.818102 density 0.820760 id 21 mass 0.044401 mean 0.820760 res_dim 2 Name: 21, dtype: object box 21 min max 2050_H2 Import 8782.0 26784.0 x23 [a] [a] up values 2050_H2 Import [1.49129367812753963e-199, 5.64447842964366e-15] x23 [0.888669000713224-100, -1.0]</pre>			Cases: 473	
	4	<pre>coverage density id mass mean res dim 0 1.00000 0.213641 0 1.00000 0.213641 0 1 1.00000 0.311809 1 0.749675 0.311809 1 2 1.00000 0.402519 2 0.449750 0.402519 1 3 0.941400 0.880752 3 0.149605 0.880752 1 4 0.940573 0.626706 4 0.217139 0.626706 2 5 0.904879 0.950391 5 0.225152 0.950391 2 6 0.879490 0.999999 6 0.095595 0.999999 2 7 0.813260 1.000000 7 0.140436 1.000000 2</pre>	<pre>coverage 0.941 density 0.880752 id 3 mass 0.249625 mean 0.880752 res_dim 1 Name: 3, dtype: object box 3 min max up values 2050_demandInterLand 13000.0 30000.0 [0.0, 0.0]</pre>			Cases: 2339	
	5	<pre>coverage density id mass mean res dim 0 1.00000 0.227158 0 1.00000 0.227158 0 1 1.00000 0.262788 1 0.749675 0.262788 1 2 1.00000 0.442111 2 0.449750 0.442111 1 3 0.805645 0.767386 3 0.249905 0.767386 1 4 0.805645 0.808081 4 0.227339 0.808081 2 5 0.803841 0.849602 5 0.225252 0.849602 2 6 0.818880 0.925706 6 0.262674 0.925706 2 7 0.845156 0.950489 7 0.195385 0.950489 2 8 0.826403 0.980451 8 0.185506 0.980451 2 9 0.792807 0.999903 9 0.141402 0.999903 2 10 0.752139 0.988163 10 0.127276 0.988163 2 11 0.710200 0.990366 11 0.115707 0.990366 2 12 0.673462 1.000000 12 0.140436 1.000000 2</pre>	<pre>coverage 0.805645 density 0.808081 id 4 mass 0.227339 mean 0.808081 res_dim 2 Name: 4, dtype: object box 4 min max up values 2050_H2 Import 0.0 29862.0 [-1.0, 0.0] 2050_demandInterLand 3888.0 8888.0 [0.0, 0.0]</pre>	<pre>coverage density id mass mean res dim 0 0.134355 0.029767 0 1.000000 0.029767 0 1 0.134355 0.044995 1 0.661572 0.044995 1 2 0.134355 0.060446 2 0.492458 0.060446 2 3 0.134355 0.090330 3 0.329538 0.090330 2 4 0.134355 0.177592 4 0.167616 0.177592 2 5 0.134354 0.237079 5 0.178159 0.237079 3 6 0.130298 0.327664 6 0.088103 0.327664 3 7 0.130298 0.348193 7 0.082909 0.348193 3 8 0.130298 0.415230 8 0.069524 0.415230 3 9 0.130298 0.458003 9 0.063031 0.458003 3 10 0.130298 0.494863 10 0.058336 0.494863 3 11 0.130298 0.534196 11 0.054041 0.534196 3 12 0.130298 0.581489 12 0.049645 0.581489 3 13 0.130298 0.642222 13 0.044951 0.642222 3 14 0.130298 0.686461 14 0.042054 0.686461 3 15 0.130298 0.726131 15 0.039756 0.726131 3 16 0.130298 0.770667 16 0.037459 0.770667 3 17 0.110911 0.878571 17 0.027969 0.878571 3</pre>	<pre>coverage 0.110911 density 0.878571 id 17 mass 0.027969 mean 0.878571 res_dim 3 Name: 17, dtype: object box 17 min max 2050_H2 Import 0.0 440.0 2050_demandInterLand 1.000000 100.000000 [-1.0, 1.0] up values [1.00000000000000e-15, 1.00000000000000e-15]</pre>	Cases: 2218	Total coverage box 1 + 2 = 0.86+0.11=0.97

6	<pre>coverage density id mass mean res_dim 0 1.000000 0.382615 0 1.000000 0.382615 0 1 1.000000 0.411081 1 0.748075 0.411081 1 2 1.000000 0.616214 2 0.508250 0.616214 1 3 0.811406 0.999302 3 0.720325 0.999302 1 4 0.810409 1.000000 4 0.188781 1.000000 2 </pre> <pre>coverage 0.811406 density 0.999282 id 3 mass 0.720325 mean 0.999282 res_dim 1 name: 3, dtype: object </pre> <pre>box 3 min max op values 2050_demandinterland 60000.0 80000.0 [0.0, -1.0] </pre>	<pre>coverage density id mass mean res_dim 0 0.188594 0.058136 0 1.000000 0.058136 0 1 0.188594 0.087876 1 0.661572 0.087876 1 2 0.188594 0.118053 2 0.492458 0.118053 2 3 0.188594 0.178967 3 0.324843 0.178967 2 4 0.188594 0.359038 4 0.161922 0.359038 2 5 0.188594 0.380392 5 0.152832 0.380392 2 6 0.188594 0.446319 6 0.130257 0.446319 2 7 0.188594 0.483389 7 0.120268 0.483389 2 8 0.188594 0.525745 8 0.110578 0.525745 2 9 0.188594 0.571148 9 0.101788 0.571148 2 10 0.188594 0.613277 10 0.094796 0.613277 2 11 0.188270 0.653543 11 0.088802 0.653543 2 12 0.187622 0.692584 12 0.083508 0.692584 2 13 0.187297 0.727960 13 0.079313 0.727960 2 14 0.186649 0.772118 14 0.074518 0.772118 2 15 0.185029 0.809929 15 0.070423 0.809929 2 16 0.183085 0.853474 16 0.066127 0.853474 2 17 0.179520 0.882166 17 0.062731 0.882166 2 18 0.173688 0.899329 18 0.059535 0.899329 2 19 0.165262 0.915619 19 0.055639 0.915619 2 20 0.158782 0.926276 20 0.052842 0.926276 2 21 0.138691 0.959641 21 0.044551 0.959641 3 22 0.132858 0.969267 22 0.042254 0.969267 3 23 0.117952 0.983784 23 0.036959 0.983784 3 </pre>	<pre>coverage 0.382615 density 0.382615 id 0 mass 1.000000 mean 0.382615 res_dim 0 name: 0, dtype: object </pre> <pre>box 0 min max op values 2050_demandinterland 0.0 1.0 [0.0, -1.0] </pre>	<p>Cases: 3086</p> <p>Total coverage box 1 + 2 = 0.81+0.18=0.99</p>	

Hydrogen time series clusters


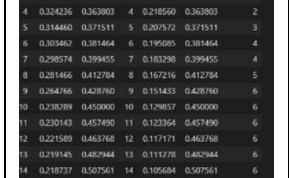
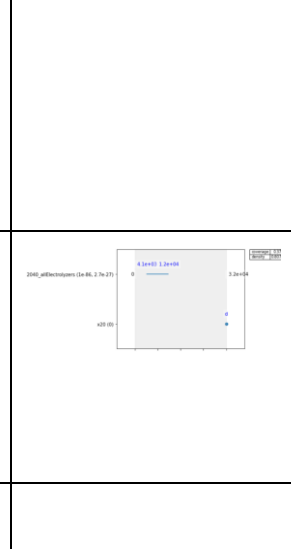
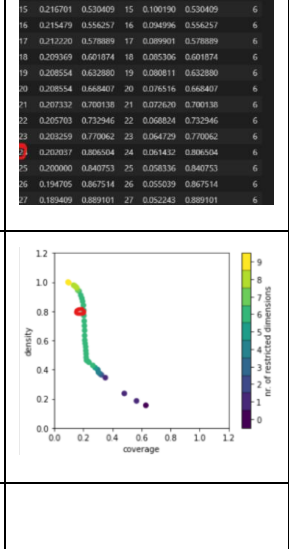
Time cluster	Box 1		Comments and PRIM																																																																																																
	<table><thead><tr><th>coverage</th><th>density</th><th>id</th><th>mass</th><th>mean</th><th>res_dim</th></tr></thead><tbody><tr><td>0</td><td>1.00000</td><td>0.053741</td><td>0</td><td>1.00000</td><td>0.053741</td></tr><tr><td>1</td><td>1.00000</td><td>0.071647</td><td>1</td><td>0.20075</td><td>0.071647</td></tr><tr><td>2</td><td>1.00000</td><td>0.107385</td><td>2</td><td>0.20040</td><td>0.107385</td></tr><tr><td>3</td><td>0.988141</td><td>0.214457</td><td>3</td><td>0.25025</td><td>0.214457</td></tr><tr><td>4</td><td>0.754647</td><td>0.321712</td><td>4</td><td>0.16061</td><td>0.321712</td></tr><tr><td>5</td><td>0.739777</td><td>0.362477</td><td>5</td><td>0.109679</td><td>0.362477</td></tr><tr><td>6</td><td>0.711896</td><td>0.429372</td><td>6</td><td>0.089102</td><td>0.429372</td></tr><tr><td>7</td><td>0.689991</td><td>0.503362</td><td>7</td><td>0.079459</td><td>0.503362</td></tr><tr><td>8</td><td>0.644981</td><td>0.517868</td><td>8</td><td>0.054240</td><td>0.517868</td></tr><tr><td>9</td><td>0.602948</td><td>0.881981</td><td>9</td><td>0.036959</td><td>0.881981</td></tr><tr><td>10</td><td>0.511599</td><td>0.900683</td><td>10</td><td>0.011565</td><td>0.900683</td></tr><tr><td>11</td><td>0.451073</td><td>0.931034</td><td>11</td><td>0.026071</td><td>0.931034</td></tr><tr><td>12</td><td>0.254364</td><td>0.980816</td><td>12</td><td>0.014285</td><td>0.980816</td></tr><tr><td>13</td><td>0.231918</td><td>0.990248</td><td>13</td><td>0.012086</td><td>0.990248</td></tr><tr><td>14</td><td>0.264329</td><td>1.00000</td><td>14</td><td>0.011088</td><td>1.00000</td></tr></tbody></table> 	coverage	density	id	mass	mean	res_dim	0	1.00000	0.053741	0	1.00000	0.053741	1	1.00000	0.071647	1	0.20075	0.071647	2	1.00000	0.107385	2	0.20040	0.107385	3	0.988141	0.214457	3	0.25025	0.214457	4	0.754647	0.321712	4	0.16061	0.321712	5	0.739777	0.362477	5	0.109679	0.362477	6	0.711896	0.429372	6	0.089102	0.429372	7	0.689991	0.503362	7	0.079459	0.503362	8	0.644981	0.517868	8	0.054240	0.517868	9	0.602948	0.881981	9	0.036959	0.881981	10	0.511599	0.900683	10	0.011565	0.900683	11	0.451073	0.931034	11	0.026071	0.931034	12	0.254364	0.980816	12	0.014285	0.980816	13	0.231918	0.990248	13	0.012086	0.990248	14	0.264329	1.00000	14	0.011088	1.00000	<pre>coverage 0.602948 density 0.881981 id 9 mass 0.036959 mean 0.881981 res_dim 3 Name: 9, dtype: object box 9 min max qp values x23 (a) (a) [9.384815601003196e-150, -1.0] x6 (f) (f) [2.914626230266373e-111, -1.0] x0 (B, C) (B, C) [7.0161440726005244e-43, -1.0]</pre> 	Cases: 539
coverage	density	id	mass	mean	res_dim																																																																																														
0	1.00000	0.053741	0	1.00000	0.053741																																																																																														
1	1.00000	0.071647	1	0.20075	0.071647																																																																																														
2	1.00000	0.107385	2	0.20040	0.107385																																																																																														
3	0.988141	0.214457	3	0.25025	0.214457																																																																																														
4	0.754647	0.321712	4	0.16061	0.321712																																																																																														
5	0.739777	0.362477	5	0.109679	0.362477																																																																																														
6	0.711896	0.429372	6	0.089102	0.429372																																																																																														
7	0.689991	0.503362	7	0.079459	0.503362																																																																																														
8	0.644981	0.517868	8	0.054240	0.517868																																																																																														
9	0.602948	0.881981	9	0.036959	0.881981																																																																																														
10	0.511599	0.900683	10	0.011565	0.900683																																																																																														
11	0.451073	0.931034	11	0.026071	0.931034																																																																																														
12	0.254364	0.980816	12	0.014285	0.980816																																																																																														
13	0.231918	0.990248	13	0.012086	0.990248																																																																																														
14	0.264329	1.00000	14	0.011088	1.00000																																																																																														
	<table><thead><tr><th>coverage</th><th>density</th><th>id</th><th>mass</th><th>mean</th><th>res_dim</th></tr></thead><tbody><tr><td>0</td><td>1.00000</td><td>0.437719</td><td>0</td><td>1.00000</td><td>0.437719</td></tr><tr><td>1</td><td>0.999544</td><td>0.503300</td><td>1</td><td>0.750075</td><td>0.503300</td></tr><tr><td>2</td><td>0.998403</td><td>0.874475</td><td>2</td><td>0.499750</td><td>0.874475</td></tr><tr><td>3</td><td>0.566864</td><td>0.993988</td><td>3</td><td>0.249625</td><td>0.993988</td></tr><tr><td>4</td><td>0.488123</td><td>0.999066</td><td>4</td><td>0.213865</td><td>0.999066</td></tr><tr><td>5</td><td>0.424236</td><td>1.00000</td><td>5</td><td>0.185486</td><td>1.00000</td></tr></tbody></table> 	coverage	density	id	mass	mean	res_dim	0	1.00000	0.437719	0	1.00000	0.437719	1	0.999544	0.503300	1	0.750075	0.503300	2	0.998403	0.874475	2	0.499750	0.874475	3	0.566864	0.993988	3	0.249625	0.993988	4	0.488123	0.999066	4	0.213865	0.999066	5	0.424236	1.00000	5	0.185486	1.00000	<pre>coverage 0.998403 density 0.874475 id 2 mass 0.49975 mean 0.874475 res_dim 1 Name: 2, dtype: object box 2 min max qp values x23 (b, a) (b, a) [0.0, -1.0]</pre> 	Cases: 4382																																																						
coverage	density	id	mass	mean	res_dim																																																																																														
0	1.00000	0.437719	0	1.00000	0.437719																																																																																														
1	0.999544	0.503300	1	0.750075	0.503300																																																																																														
2	0.998403	0.874475	2	0.499750	0.874475																																																																																														
3	0.566864	0.993988	3	0.249625	0.993988																																																																																														
4	0.488123	0.999066	4	0.213865	0.999066																																																																																														
5	0.424236	1.00000	5	0.185486	1.00000																																																																																														
	<table><thead><tr><th>coverage</th><th>density</th><th>id</th><th>mass</th><th>mean</th><th>res_dim</th></tr></thead><tbody><tr><td>0</td><td>1.00000</td><td>0.255419</td><td>0</td><td>1.00000</td><td>0.255419</td></tr><tr><td>1</td><td>0.999609</td><td>0.340573</td><td>1</td><td>0.748675</td><td>0.340573</td></tr><tr><td>2</td><td>0.994134</td><td>0.507791</td><td>2</td><td>0.500050</td><td>0.507791</td></tr><tr><td>3</td><td>0.576026</td><td>0.998401</td><td>3</td><td>0.249925</td><td>0.998401</td></tr><tr><td>4</td><td>0.861527</td><td>0.999546</td><td>4</td><td>0.220108</td><td>0.999546</td></tr><tr><td>5</td><td>0.742276</td><td>1.00000</td><td>5</td><td>0.189591</td><td>1.00000</td></tr></tbody></table> 	coverage	density	id	mass	mean	res_dim	0	1.00000	0.255419	0	1.00000	0.255419	1	0.999609	0.340573	1	0.748675	0.340573	2	0.994134	0.507791	2	0.500050	0.507791	3	0.576026	0.998401	3	0.249925	0.998401	4	0.861527	0.999546	4	0.220108	0.999546	5	0.742276	1.00000	5	0.189591	1.00000	<pre>coverage 0.976926 density 0.998401 id 3 mass 0.249925 mean 0.998401 res_dim 1 Name: 3, dtype: object box 3 min max qp values x23 (c) (c) [0.0, -1.0]</pre> 	Cases: 2557																																																						
coverage	density	id	mass	mean	res_dim																																																																																														
0	1.00000	0.255419	0	1.00000	0.255419																																																																																														
1	0.999609	0.340573	1	0.748675	0.340573																																																																																														
2	0.994134	0.507791	2	0.500050	0.507791																																																																																														
3	0.576026	0.998401	3	0.249925	0.998401																																																																																														
4	0.861527	0.999546	4	0.220108	0.999546																																																																																														
5	0.742276	1.00000	5	0.189591	1.00000																																																																																														



380 kV TenneT PRIM-analysis – with subgroups and no factor x34 and DAC and overload classes

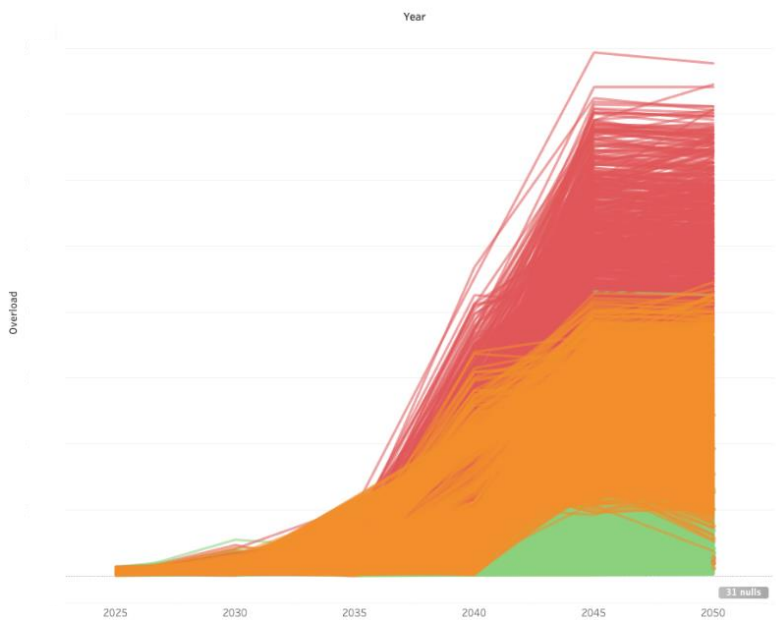
Year	Class	Box 1		Box 2		Comments and PRIM
2025	1					Cases: 68 No PRIM box found
	2	<pre>coverage density id mass mean res_dim 0 1.00000 0.993108 0 1.00000 0.993108 0 1 0.37779 1.00000 1 0.37488 1.00000 1</pre>	<pre>coverage density id mass mean res_dim 0 0.622410 0.618120 0 1.00000 0.618120 0 1 0.622410 0.988972 1 0.717810 0.861119 1 2 0.622410 0.988972 2 0.625012 0.988972 1 3 0.460618 0.991277 3 0.463484 0.991277 2 4 0.394790 0.992415 4 0.395065 0.992415 3 5 0.066486 0.998409 5 0.066127 0.998409 4 6 0.052505 1.000000 6 0.052143 1.000000 4</pre>	<pre>coverage density id mass mean res_dim 0 0.622410 0.618120 0 1.00000 0.618120 0 1 0.622410 0.988972 1 0.717810 0.861119 1 2 0.622410 0.988972 2 0.625012 0.988972 1 3 0.460618 0.991277 3 0.463484 0.991277 2 4 0.394790 0.992415 4 0.395065 0.992415 3 5 0.066486 0.998409 5 0.066127 0.998409 4 6 0.052505 1.000000 6 0.052143 1.000000 4</pre>	Cases: 9942 Total coverage box 1 + 2 = 0.62+0.37=0.99	
2030	1					Cases: 2 No PRIM box found
	2	<pre>coverage density id mass mean res_dim 0 1.00000 0.882230 0 1.00000 0.882230 0 1 0.924001 0.988972 1 0.924001 0.988972 1 2 0.522536 0.958364 2 0.508649 0.958364 1 3 0.524804 0.962562 3 0.488272 0.962562 2 4 0.419273 0.963484 4 0.415204 0.963484 2 5 0.424411 0.969184 5 0.378481 0.969184 2 6 0.488375 0.968487 6 0.467862 0.968487 2 7 0.368386 0.988529 7 0.338624 0.988529 1 8 0.364837 0.999068 8 0.321446 0.999068 4 9 0.354400 1.000000 9 0.348404 1.000000 1</pre>	<pre>coverage density id mass mean res_dim 0 0.761000 0.999999 0 0.761000 0.999999 0 1 0.761000 0.999999 1 0.761000 0.999999 0 2 0.761000 0.999999 2 0.761000 0.999999 0 3 0.761000 0.999999 3 0.761000 0.999999 0 4 0.761000 0.999999 4 0.761000 0.999999 0 5 0.761000 0.999999 5 0.761000 0.999999 0 6 0.761000 0.999999 6 0.761000 0.999999 0 7 0.761000 0.999999 7 0.761000 0.999999 0 8 0.761000 0.999999 8 0.761000 0.999999 0 9 0.761000 0.999999 9 0.761000 0.999999 0</pre>		Cases: 8832	
	3	<pre>coverage density id mass mean res_dim 0 1.00000 0.117471 0 1.00000 0.117471 0 1 0.986395 0.935361 1 0.925112 0.935361 1 2 0.528819 0.893426 2 0.525362 0.893426 2 3 0.419173 0.538851 3 0.396987 0.538851 3 4 0.354392 0.534380 4 0.337220 0.534380 4 5 0.258801 0.447101 5 0.247340 0.447101 4</pre>				Cases: 1176 Too low density for results

2035	1					Cases: 64
	2	<pre>coverage density id mass mean res_dim 0 1.000000 0.561379 0 1.000000 0.561379 0 1 0.924880 0.710054 1 0.750075 0.710054 1 2 0.983003 0.936007 2 0.983003 0.936007 1 3 0.784425 0.933053 3 0.784425 0.933053 2 4 0.738007 0.941861 4 0.738007 0.941861 2 5 0.702017 0.940122 5 0.702017 0.940122 2 6 0.627389 0.952369 6 0.627389 0.952369 2 7 0.647301 0.958025 7 0.647301 0.958025 2 8 0.615108 0.962149 8 0.615108 0.962149 2 9 0.528198 0.963426 9 0.528198 0.963426 2 10 0.555106 0.968024 10 0.555106 0.968024 2 11 0.524801 0.973053 11 0.524801 0.973053 2 12 0.482404 0.977404 12 0.482404 0.977404 2 13 0.443003 0.978012 13 0.443003 0.978012 2 14 0.150000 0.980679 14 0.150000 0.980679 1 15 0.114109 0.993370 15 0.114109 0.993370 2 16 0.101011 0.998408 16 0.101011 0.998408 2 17 0.102101 1.000000 17 0.102101 1.000000 4</pre> <pre>coverage 0.802655 density 0.906637 id 2 mass 0.49965 mean 0.906637 res_dim 1 Name: 2, dtype: object box 2 min max qp values x20 (b, a) (b, a) [0.0, -1.0]</pre> <pre>coverage density id mass mean res_dim 0 0.197345 0.111377 0 1.000000 0.111377 0 1 0.197345 0.148488 1 0.750075 0.148488 1 2 0.197345 0.222599 2 0.500350 0.222599 1 3 0.197345 0.380950 3 0.467785 0.380950 2 4 0.197345 0.253236 4 0.439816 0.253236 2 5 0.197345 0.266619 5 0.417740 0.266619 2 6 0.197345 0.283139 6 0.393367 0.283139 2 7 0.197345 0.309945 7 0.370093 0.309945 2 8 0.197345 0.318662 8 0.349516 0.318662 2 9 0.197345 0.337266 9 0.330237 0.337266 2 10 0.197168 0.350084 10 0.310758 0.350084 2 11 0.196814 0.376949 11 0.294676 0.376949 2 12 0.196814 0.399569 12 0.277994 0.399569 2 13 0.195575 0.415402 13 0.263810 0.415402 2 14 0.194336 0.440787 14 0.240056 0.440787 2 15 0.193628 0.463363 15 0.235941 0.463363 2 16 0.137876 0.669169 16 0.117870 0.669169 2 17 0.156637 0.688671 17 0.111977 0.688671 2 18 0.154336 0.713346 18 0.106283 0.713346 2 19 0.150619 0.739479 19 0.099900 0.739479 2 20 0.128673 0.767807 20 0.084596 0.767807 2 21 0.125664 0.792411 21 0.089502 0.792411 2 22 0.121593 0.807286 22 0.085006 0.807286 2 23 0.061062 0.912698 23 0.037258 0.912698 3</pre> <pre>coverage 0.12015 density 0.889504 id 11 mass 0.115879 mean 0.889504 res_dim 2 Name: 11, dtype: object box 11 min max qp values x20 (b, a) (b, a) [0.0, -1.0]</pre>	Cases: 5650			
						Total coverage box 1+ 2 = 0.8+0.11= 0.91
	3	<pre>coverage density id mass mean res_dim 0 1.000000 0.767006 0 1.000000 0.767006 0 1 0.952488 0.339660 1 0.750075 0.339660 1 2 0.886305 0.480571 2 0.500350 0.480571 1 3 0.855702 0.477945 3 0.467785 0.477945 2 4 0.903006 0.571732 4 0.251341 0.571732 2 5 0.484424 0.580515 5 0.219059 0.580515 3 6 0.466891 0.599136 6 0.208071 0.599136 3 7 0.464846 0.620881 7 0.191802 0.620881 3 8 0.458861 0.645490 8 0.183789 0.645490 3 9 0.451178 0.679407 9 0.177305 0.679407 3 10 0.442948 0.703204 10 0.168015 0.703204 3 11 0.435991 0.728627 11 0.159325 0.728627 3 12 0.431027 0.762387 12 0.151134 0.762387 3 13 0.421200 0.788377 13 0.143542 0.788377 3 14 0.408756 0.800440 14 0.138150 0.800440 3 15 0.394867 0.808176 15 0.132860 0.808176 3 16 0.364579 0.818640 16 0.117969 0.818640 3 17 0.353361 0.838158 17 0.112776 0.838158 3 18 0.337014 0.849485 18 0.107062 0.849485 3 19 0.332100 0.868608 19 0.101588 0.868608 3 20 0.305894 0.872050 20 0.094394 0.872050 3 21 0.294435 0.871050 21 0.091300 0.871050 3 22 0.077308 0.947115 22 0.020777 0.947115 4</pre> <pre>coverage 0.408156 density 0.80044 id 14 mass 0.13615 mean 0.80044 res_dim 3 Name: 14, dtype: object box 14 min max x20 (c) (c) 2035_allElectrolyzers 520.0 3403.0 2035_allCogens 667.5 824.0</pre>	Cases: 2673			
	4	<pre>coverage density id mass mean res_dim 0 1.000000 0.143232 0 1.000000 0.143232 0 1 0.988916 0.213020 1 0.750075 0.213020 1 2 0.977217 0.316830 2 0.500350 0.316830 1 3 0.880171 0.520142 3 0.250425 0.520142 1 4 0.794991 0.542603 4 0.237939 0.542603 2 5 0.799179 0.571112 5 0.224452 0.571112 2 6 0.793103 0.601588 6 0.213665 0.601588 2 7 0.791256 0.643071 7 0.203077 0.643071 2 8 0.791256 0.665458 8 0.192088 0.665458 2 9 0.786809 0.704564 9 0.182098 0.704564 2 10 0.786810 0.744512 10 0.173409 0.744512 2 11 0.778841 0.768997 11 0.164319 0.768997 2 12 0.768810 0.801546 12 0.155029 0.801546 2 13 0.748021 0.834049 13 0.147038 0.834049 2 14 0.722217 0.847490 14 0.138247 0.847490 2 15 0.708144 0.875321 15 0.131795 0.875321 2 16 0.634802 0.914007 16 0.112676 0.914007 3 17 0.610222 0.925303 17 0.106962 0.925303 3 18 0.588670 0.948020 18 0.101588 0.948020 3 19 0.572794 0.970794 19 0.095102 0.970794 4 20 0.494758 0.964386 20 0.083008 0.964386 4 21 0.475369 0.967419 21 0.079712 0.967419 5 22 0.443966 0.971098 22 0.074110 0.971098 5 23 0.411335 0.977856 23 0.069424 0.977856 5 24 0.394812 0.984709 24 0.064525 0.984709 5 25 0.372768 0.989539 25 0.061333 0.989539 5 26 0.355891 0.991424 26 0.058136 0.991424 6</pre> <pre>coverage 0.10001 density 0.889504 id 11 mass 0.115879 mean 0.889504 res_dim 2 Name: 11, dtype: object box 11 min max qp values x20 (b, a) (b, a) [0.0, -1.0]</pre>	Cases: 1624			

4			Cases: 2455
5			Cases: 1444

TenneT 380 kV time series clusters, low/medium/high

Total:

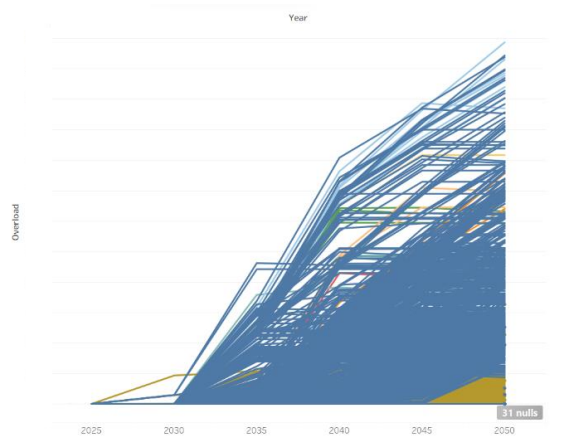


Time cluster	Box 1		Comments and PRIM																																																																																																																																																		
Low (green)	<table><thead><tr><th></th><th>coverage</th><th>density</th><th>id</th><th>mass</th><th>mean</th><th>res_dim</th></tr></thead><tbody><tr><td>0</td><td>1.000000</td><td>0.730696</td><td>0</td><td>1.000000</td><td>0.730696</td><td>0</td></tr><tr><td>1</td><td>0.970608</td><td>0.766077</td><td>1</td><td>0.925782</td><td>0.766077</td><td>1</td></tr><tr><td>2</td><td>0.948599</td><td>0.792395</td><td>2</td><td>0.874738</td><td>0.792395</td><td>1</td></tr><tr><td>3</td><td>0.927409</td><td>0.818829</td><td>3</td><td>0.827590</td><td>0.818829</td><td>1</td></tr><tr><td>4</td><td>0.795762</td><td>0.932554</td><td>4</td><td>0.623514</td><td>0.932554</td><td>2</td></tr><tr><td>5</td><td>0.773206</td><td>0.955567</td><td>5</td><td>0.591250</td><td>0.955567</td><td>2</td></tr><tr><td>6</td><td>0.721941</td><td>0.968103</td><td>6</td><td>0.544901</td><td>0.968103</td><td>3</td></tr><tr><td>7</td><td>0.658783</td><td>0.973142</td><td>7</td><td>0.494656</td><td>0.973142</td><td>4</td></tr><tr><td>8</td><td>0.627204</td><td>0.976378</td><td>8</td><td>0.469384</td><td>0.976378</td><td>5</td></tr><tr><td>9</td><td>0.595899</td><td>0.978451</td><td>9</td><td>0.445010</td><td>0.978451</td><td>6</td></tr><tr><td>10</td><td>0.564867</td><td>0.980308</td><td>10</td><td>0.421037</td><td>0.980308</td><td>6</td></tr><tr><td>11</td><td>0.534245</td><td>0.982403</td><td>11</td><td>0.397363</td><td>0.982403</td><td>7</td></tr><tr><td>12</td><td>0.360355</td><td>0.992096</td><td>12</td><td>0.265408</td><td>0.992096</td><td>7</td></tr><tr><td>13</td><td>0.342857</td><td>0.993661</td><td>13</td><td>0.252123</td><td>0.993661</td><td>7</td></tr><tr><td>14</td><td>0.326042</td><td>0.994994</td><td>14</td><td>0.239437</td><td>0.994994</td><td>8</td></tr><tr><td>15</td><td>0.309364</td><td>0.996039</td><td>15</td><td>0.226950</td><td>0.996039</td><td>8</td></tr><tr><td>16</td><td>0.285988</td><td>0.997616</td><td>16</td><td>0.209470</td><td>0.997616</td><td>9</td></tr><tr><td>17</td><td>0.266029</td><td>0.998461</td><td>17</td><td>0.194686</td><td>0.998461</td><td>9</td></tr><tr><td>18</td><td>0.243062</td><td>0.999438</td><td>18</td><td>0.177705</td><td>0.999438</td><td>10</td></tr><tr><td>19</td><td>0.229802</td><td>1.000000</td><td>19</td><td>0.167915</td><td>1.000000</td><td>10</td></tr></tbody></table> <div><div>coverage: 0.948599 density: 0.792395 id: 2 mass: 0.874738 mean: 0.792395 res_dim: 1 Name: 2, dtype: object</div><div><div>box 2 \</div><div>min max</div><div>2050_ElectrolyzerRefinery_PERWIJN 250.0 13132.5</div></div></div> <div></div> <div></div>		coverage	density	id	mass	mean	res_dim	0	1.000000	0.730696	0	1.000000	0.730696	0	1	0.970608	0.766077	1	0.925782	0.766077	1	2	0.948599	0.792395	2	0.874738	0.792395	1	3	0.927409	0.818829	3	0.827590	0.818829	1	4	0.795762	0.932554	4	0.623514	0.932554	2	5	0.773206	0.955567	5	0.591250	0.955567	2	6	0.721941	0.968103	6	0.544901	0.968103	3	7	0.658783	0.973142	7	0.494656	0.973142	4	8	0.627204	0.976378	8	0.469384	0.976378	5	9	0.595899	0.978451	9	0.445010	0.978451	6	10	0.564867	0.980308	10	0.421037	0.980308	6	11	0.534245	0.982403	11	0.397363	0.982403	7	12	0.360355	0.992096	12	0.265408	0.992096	7	13	0.342857	0.993661	13	0.252123	0.993661	7	14	0.326042	0.994994	14	0.239437	0.994994	8	15	0.309364	0.996039	15	0.226950	0.996039	8	16	0.285988	0.997616	16	0.209470	0.997616	9	17	0.266029	0.998461	17	0.194686	0.998461	9	18	0.243062	0.999438	18	0.177705	0.999438	10	19	0.229802	1.000000	19	0.167915	1.000000	10	Cases: 7314
	coverage	density	id	mass	mean	res_dim																																																																																																																																															
0	1.000000	0.730696	0	1.000000	0.730696	0																																																																																																																																															
1	0.970608	0.766077	1	0.925782	0.766077	1																																																																																																																																															
2	0.948599	0.792395	2	0.874738	0.792395	1																																																																																																																																															
3	0.927409	0.818829	3	0.827590	0.818829	1																																																																																																																																															
4	0.795762	0.932554	4	0.623514	0.932554	2																																																																																																																																															
5	0.773206	0.955567	5	0.591250	0.955567	2																																																																																																																																															
6	0.721941	0.968103	6	0.544901	0.968103	3																																																																																																																																															
7	0.658783	0.973142	7	0.494656	0.973142	4																																																																																																																																															
8	0.627204	0.976378	8	0.469384	0.976378	5																																																																																																																																															
9	0.595899	0.978451	9	0.445010	0.978451	6																																																																																																																																															
10	0.564867	0.980308	10	0.421037	0.980308	6																																																																																																																																															
11	0.534245	0.982403	11	0.397363	0.982403	7																																																																																																																																															
12	0.360355	0.992096	12	0.265408	0.992096	7																																																																																																																																															
13	0.342857	0.993661	13	0.252123	0.993661	7																																																																																																																																															
14	0.326042	0.994994	14	0.239437	0.994994	8																																																																																																																																															
15	0.309364	0.996039	15	0.226950	0.996039	8																																																																																																																																															
16	0.285988	0.997616	16	0.209470	0.997616	9																																																																																																																																															
17	0.266029	0.998461	17	0.194686	0.998461	9																																																																																																																																															
18	0.243062	0.999438	18	0.177705	0.999438	10																																																																																																																																															
19	0.229802	1.000000	19	0.167915	1.000000	10																																																																																																																																															

<p>Medium (orange)</p>	<table><thead><tr><th></th><th>coverage</th><th>density</th><th>id</th><th>mass</th><th>mean</th><th>res_dim</th></tr></thead><tbody><tr><td>0</td><td>1.000000</td><td>0.204575</td><td>0</td><td>1.000000</td><td>0.204575</td><td>0</td></tr><tr><td>1</td><td>1.000000</td><td>0.204698</td><td>1</td><td>0.999401</td><td>0.204698</td><td>1</td></tr><tr><td>2</td><td>0.902832</td><td>0.246369</td><td>2</td><td>0.749675</td><td>0.246369</td><td>2</td></tr><tr><td>3</td><td>0.803223</td><td>0.328474</td><td>3</td><td>0.500250</td><td>0.328474</td><td>2</td></tr><tr><td>4</td><td>0.649414</td><td>0.530515</td><td>4</td><td>0.250425</td><td>0.530515</td><td>2</td></tr><tr><td>5</td><td>0.326172</td><td>0.730055</td><td>5</td><td>0.091399</td><td>0.730055</td><td>3</td></tr><tr><td>6</td><td>0.103027</td><td>0.967890</td><td>6</td><td>0.021776</td><td>0.967890</td><td>4</td></tr><tr><td>7</td><td>0.098633</td><td>0.975845</td><td>7</td><td>0.020677</td><td>0.975845</td><td>5</td></tr><tr><td>8</td><td>0.094238</td><td>0.984694</td><td>8</td><td>0.019578</td><td>0.984694</td><td>6</td></tr><tr><td>9</td><td>0.089844</td><td>0.989247</td><td>9</td><td>0.018580</td><td>0.989247</td><td>7</td></tr><tr><td>10</td><td>0.084961</td><td>0.994286</td><td>10</td><td>0.017481</td><td>0.994286</td><td>8</td></tr><tr><td>11</td><td>0.079590</td><td>1.000000</td><td>11</td><td>0.016282</td><td>1.000000</td><td>9</td></tr></tbody></table>		coverage	density	id	mass	mean	res_dim	0	1.000000	0.204575	0	1.000000	0.204575	0	1	1.000000	0.204698	1	0.999401	0.204698	1	2	0.902832	0.246369	2	0.749675	0.246369	2	3	0.803223	0.328474	3	0.500250	0.328474	2	4	0.649414	0.530515	4	0.250425	0.530515	2	5	0.326172	0.730055	5	0.091399	0.730055	3	6	0.103027	0.967890	6	0.021776	0.967890	4	7	0.098633	0.975845	7	0.020677	0.975845	5	8	0.094238	0.984694	8	0.019578	0.984694	6	9	0.089844	0.989247	9	0.018580	0.989247	7	10	0.084961	0.994286	10	0.017481	0.994286	8	11	0.079590	1.000000	11	0.016282	1.000000	9	<div><div>coverage: 0.326172 density: 0.730055 id: 5 mass: 0.091399 mean: 0.730055 res_dim: 3 Name: 5, dtype: object</div><div><div>box 5</div><div><div>min</div><div>max</div><div>qp values</div></div><div>2050_WindFarm_MW 22100.0 26100.0 [2.807644030483965e-187, -1.0] 2050_GeneralDemand_EUPER 113.0 158.0 [2.807644030483965e-187, -1.0] 2050_Electrolysis_EUPER 226.0 226.0 [0.517123146870044, 1.0]</div></div></div>	<p>Cases: 2048</p>
	coverage	density	id	mass	mean	res_dim																																																																																								
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<p>High (red)</p>			<p>Comment: outcome of 52 cases in the peeling trajectory with a high number of restricted dimensions so no explanation available</p> <p>Cases: 648</p>																																																																																											

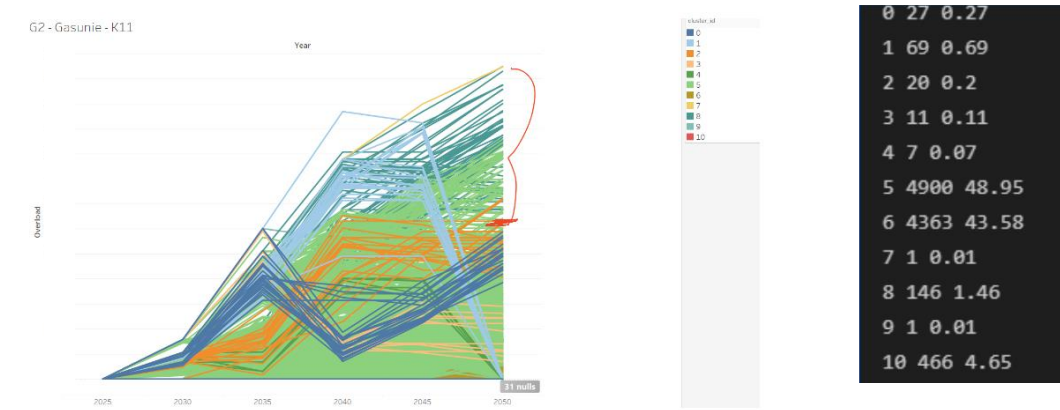
PRIM-results ODO-network

The following timeseries clustering was made based on the clustering algorithm:

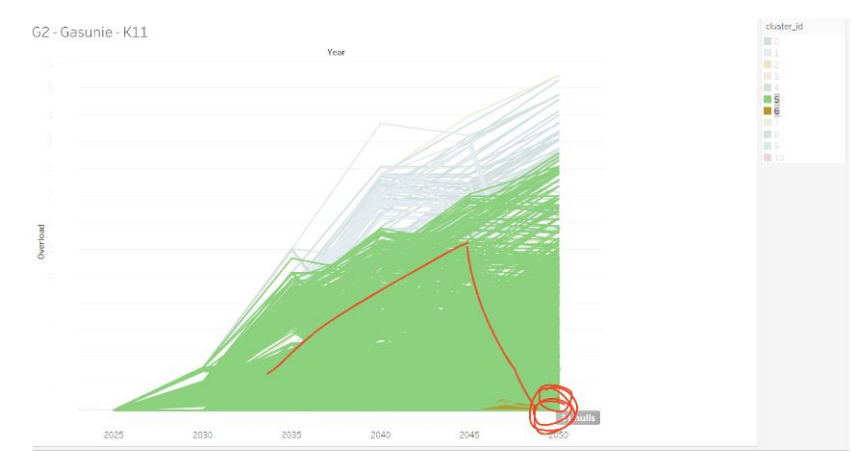


Conclusion: no PRIM-boxes found. Potential causes: lack of overload in the ODO-network and inappropriate time series clustering algorithm.

PRIM-results NODO



Almost all cases are in cluster 5 and 6:



Conclusion: no PRIM-boxes found. Potential causes: lack of overload in the NODO-network and inappropriate time series clustering algorithm

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