

The transition of a natural gas network to a hydrogen network

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THE TRANSITION OF A NATURAL GAS NETWORK TO A HYDROGEN NETWORK

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PREFACE

“The transition of a natural gas network to a hydrogen network” is the title of my master thesis. With this final work, I will conclude my time as a student at Delft University of Technology and complete my master Complex Systems Engineering and Management. I want to thank my supervisors for all their guidance, feedback and support during the whole process of my graduation.

Firstly I want to thank Emile Chappin. Thank you for all your critical, but above all, constructive feedback. I really appreciate the fact that you always took the time to read my work thoroughly and provide me with new insights. During my bachelor thesis I already had the pleasure to have you as my supervisor and I am glad that I got the chance to extend that collaboration in my master thesis.

Martijn Warnier, stories about you as great, involved, challenging and motivating supervisor resonate in TPM and I can confirm that all these stories are true. I really need to thank you for all your insights, patients with my programming skills and your ability to trigger me to perform better than I thought I could. I am glad I had you as my mentor.

Then to my friends, my parents, sister and Ingmar, thank you for the motivation, the support, the feedback, showing interest in my research but also for providing me with distraction when I needed this. With the exception of the first two weeks, I wrote my entire thesis during the Corona crisis. This was quite challenging, but it did help me place everything in perspective, and it showed me my ability to adapt to situations I do not control. I have to apologize to my housemates for using a big part of the internet capacity during my online project meetings in Zoom.

With this thesis, my time as a student in Delft has officially come to an end. I can look back on seven fantastic years where I got the opportunity to develop myself on so many different levels. I look forward to see what the future holds, and hope to keep contact with the many friends who accompanied me on this journey.

Enjoy reading!

Anne de Boer
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EXECUTIVE SUMMARY

Hydrogen is considered to be a promising replacement of fossil fuel-based energy for the future energy supply. The possibilities to use hydrogen are extensive; hydrogen can provide high temperatures for industrial processes, produce electricity, heat buildings and be a fuel for the mobility sector without releasing carbon. In order to implement hydrogen transition in the current economy, a hydrogen infrastructure needs to be established.

Prior research has pointed out that after certain alterations, the current natural gas infrastructure can transport hydrogen. The natural gas infrastructure in the Netherlands is extensive, and the capacity is big enough to satisfy the Dutch hydrogen need. Additionally, considerable costs can be saved if the natural gas network is used. The costs to adapt natural gas pipelines to transport hydrogen is ten times lower than the costs of constructing new hydrogen pipelines.

The common approach for the design of the new hydrogen infrastructure is optimisation. However, prior research in regard to network evolution has indicated that infrastructure evolution is characterised by path-dependency, lock-ins and network effects. These factors are neutralised in the current optimisation methods. It is reasonable to presume that these factors of network evolution will also have an impact on the network transition that is based on an existing network. The first reason to assume this is that the development of the hydrogen network is estimated to take 30 years, in which other developments are likely to occur. Second, investments that are made, are locked in the new infrastructures, as expenses made cannot be spent again in a different manner. Furthermore, the investments made determine future options for investment.

Research into the transition of one network, which is based on an existing network, remains uncharted. This thesis will evaluate the effect of different tactics and strategies on the transition of a network from fulfilling one purpose, distributing natural gas, to another, distributing hydrogen while taking path dependency into account. An agent-based model that applies rule-based behaviour is constructed to answer the main research question, which reads as follows:

How do different transition strategies for the transition of a natural gas infrastructure to a (partial) hydrogen infrastructure perform over time?

To create this agent-based network, a representation of a network was made with several components, so-called nodes and edges. Nodes are the entry or exit points of the network, the production sites of gas (either natural gas or hydrogen), heavy industry, energy generators or the points where the gas is converted from the transmission network to the distribution network. All nodes have a utility score based on the type of node, and the distance of

the node to the closest hydrogen point in the network. This allows for the calculation of the utility score of a specific edge. Edges are the connection between the nodes and represent existing pipelines, potential new pipelines or temporary connections in the form of tanks.

The effect of four tactical choices on the transition behaviour of the network is tested in regard to the costs of the transition, the volume hydrogen that is delivered to the network and the volume hydrogen that is exported. The following tactical choices are evaluated:

- Prioritise the network transition on local optimisation criteria,
- Including new pipe to be constructed in the existing graph,
- Prioritising the export of both hydrogen and natural gas,
- Allocate the available budget over time in different patterns.

Based on the results of experimenting with the tactics, the following four strategies are formed:

- Minimise cost, prioritise the export of both hydrogen and natural gas,
- Minimise cost, no prioritisation of the export of hydrogen and natural gas,
- Maximise hydrogen delivery, prioritise the export of both hydrogen and natural gas,
- Maximise hydrogen delivery, no prioritisation of the export of hydrogen and natural gas.

These strategies are applied to the random network developed for this thesis, and on topologies based on the Netherlands, Belgium and the United Kingdom.

The results show that the strategies focusing on the minimisation of costs structurally have lower expenses than the strategies that maximise hydrogen delivery. However, in the case of the random starting topology and the topology based on Belgium, this is always at the expense of the hydrogen delivery as these strategies cause lock-ins. Prioritising the export of hydrogen and natural gas delays the developments of lock-ins and is therefore not only beneficial for the hydrogen export, but also for the volume of hydrogen delivered in the system. The topologies based on the Netherlands and the United Kingdom are less susceptible to lock-ins.

There are situations in the topologies based on the Netherlands and the United Kingdom where the same volume of hydrogen is delivered in the strategies based on maximising hydrogen delivery. In these cases, minimising costs is the optimal strategy. In other situations, the hydrogen delivery in the strategies based on minimising costs is lower. In that case, a trade-off needs to be made between the hydrogen delivery and costs.

The experiments in this thesis have led to the seven insights that should be considered in the realisation of a hydrogen infrastructure.

1. The characteristics of a network are important. Best practices in one infrastructure should not be copied without any further consideration.
2. Purely adapting the existing network does not lead to the best outcome, and therefore the option for constructing new pipes on some critical points should be considered. The construction of new pipes helps to overcome lock-ins and therefore has a positive effect on the system outcome.
3. It is best to invest maximally according to the available budget, the maximal capacity of the system and the foreseen future. With this, the system can benefit the longest from these investments and changes to the network.
4. Be reluctant about the network transition to certain geographic areas where the contribution is limited to only a small part of the network.
5. It is wise to determine minimal thresholds for the performance of the system to ensure that the system does not minimise costs at the expense of other key performance indicators.
6. Prioritise the flow of export and import of natural gas and hydrogen through the country. Not only does the country financially benefit from an export corridor, there are also positive effects for the network as this export corridor ensures an available hydrogen connection throughout the country.
7. Specific for the topology based on the Netherlands and the United Kingdom; there are situations where the strategy that minimises costs reaches the same hydrogen delivery as the strategy that maximises the hydrogen delivery. This reinforces the first insight. The specific situation and location of nodes should be reviewed in order to determine the optimal strategy.

There are some limitations to the model created in this thesis. First, the local optimisation is done based on the utility of a pipe. This utility has a direct connection to the utility of the nodes it is connected to. Calculating the pipe utility as the added gain for the whole system would strengthen this model's approach. Second, the average betweenness centrality and closeness centrality does not show a relation with the effectiveness of the tactics and strategies. This is probably because centrality measures are calculated for the whole system and not for the flows of hydrogen and/or natural gas. It is recommended to recalculate the two centrality measures, taking the gas flows into account, and observe whether there is a relation that can be used as a predictor for the effect of tactics and strategies.

In this thesis, a system-level approach with a step for step transition is used. Network evolutionary elements like path-dependency, lock-ins and network effects were taken into account. Including these elements of network transition, led to seven insights regarding the process of (network) evolution, compared to overall system optimisation. These seven insights should be considered when formulating an approach for the realisation of a hydrogen infrastructure.

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1 | INTRODUCTION

With the signing of the Paris agreement, 195 countries committed to fight global warming by keeping the increase in temperature below 2 degrees and with an even more ambitious target of keeping it below 1.5 degrees (United Nations Framework Convention on Climate Change, 2015). The emission targets require an energy transition where the current fossil fuel-based energy systems make place for new, carbon-neutral or carbon-free systems. These new systems will focus on producing green or carbon-free electricity and on converting green generated electrons into green molecules, such as hydrogen (Gasunie and TenneT, 2019).

1.1 PROBLEM DEFINITION

1.1.1 Hydrogen in a system function

Hydrogen is considered to be a promising potential energy carrier for the future energy supply. The possibilities for hydrogen are extensive; hydrogen can create high temperatures for industrial processes, produce electricity, heat buildings and be a fuel for the mobility sector without releasing any carbon emissions.

Hydrogen is flexible in terms of production methods and resources, applicable in various sectors, able to be stored and has the opportunity to be scaled up. Hydrogen therefore has the potential to fulfil a system function in the new energy system (van der Linde and van Leeuwen, 2019). An energy carrier with a system function has the opportunity to connect different energy functions with a guaranteed supply, and guaranteed market access for producers, suppliers and consumers (van der Linde and van Leeuwen, 2019). When hydrogen is capable of fulfilling a system function, a robust energy system is realised.

1.1.2 The Dutch Hydrogen ambitions

The Dutch government has expressed its ambition to maintain their role of being in the frontline of innovation. This is in line with the Netherlands having a knowledge-based economy and aspiring an internationally leading position in a new hydrogen economy (Kabinet Rutte III, 2019).

The conditions for the Netherlands to keep this are favourable with a big process industry, large potential for offshore wind energy generation and an enhanced natural gas infrastructure (Kabinet Rutte III, 2019).

It is expected that before 2030 small hydrogen projects will develop, and after

that, hydrogen will start to be used on a larger scale (van der Linde and van Leeuwen, 2019). To realise this, a backbone for the hydrogen infrastructure needs to be ready by 2030 (van der Linde and van Leeuwen, 2019). When an infrastructure backbone is available, the hydrogen economy can benefit from positive network effects.

1.2 RESEARCH OBJECTIVE

The natural gas infrastructure in the Netherlands is extensive. This infrastructure has the capacity that would be sufficient to accommodate the hydrogen need in the Dutch energy system. After some adaptations, the natural gas network will be suitable to distribute hydrogen (Gasunie and TenneT, 2019). However, natural gas is seen as a transition fuel for lower carbon emissions (Stapersma, 2019), meaning that the demand for natural gas will not be reduced to the extent that the natural gas infrastructure is not needed anymore in 2030.

Using the current natural gas infrastructure for the distribution of hydrogen would reduce the cost of the already expensive energy transition. However, an infrastructure cannot distribute both natural gas and hydrogen at the same time. With this, a dilemma arises that we now call the transition dilemma. This thesis will try to find answers on how to deal with this transition dilemma. It aims to give more insights into the fundamental principles of how this transition can evolve and how strategies can influence this transition.

1.3 RESEARCH SCOPE

To get a better understanding of the fundamental principles that drive this transition, this research will be executed on a system level to uncover the relevant factors. In this sense, this research does not intend to calculate and optimise the transition of a specific hydrogen infrastructure. However, it aims to get insight in the processes on a general level. This allows for more generalised insight that is not specific for a certain (part of an) infrastructure. With this system-level approach, it is possible to investigate different strategies based on the network characteristics and unravel the extent to which different strategies impact the transition of the new infrastructure, and receive insights to how networks transition based on an established infrastructure.

With a better understanding of how an infrastructure transition, lessons can be drawn that can be applied to the development of the hydrogen infrastructure. These insights can improve this development in such a way that is beneficial to the energy transition.

1.4 OUTLINE OF THIS THESIS

This first chapter aims to introduce the topic and describe the scope of this thesis. In chapter 2, a literature review is performed to identify what principles are not yet researched and where additional research needs to be done. Chapter 3 Introduces the main research question, sub-questions and explains the methodology followed. In the 4th chapter, the first research question is answered, and more insight is gained on the chosen representation of the network. In chapter 5, the conceptual model is introduced that is used for the modelling process. This conceptual model is then formalised in chapter 6. The results of different scenarios for the model are presented in chapter 7. Further analysis of the results is performed in chapter 8. The findings of this research are then reflected upon and discussed in chapter 9 The synopsis and the importance of this thesis for society and the scientific field are discussed in chapter 10.

2 | LITERATURE REVIEW

A literature review has been done to research the possibilities and the way the transition of natural gas to a hydrogen infrastructure evolves. The goal of this literature search is to determine what research has been done and to identify gaps in knowledge concerning the transition.

2.1 A HYDROGEN INFRASTRUCTURE

Hydrogen can be transported in various ways. As a gas, it is typically transported through pipelines or in gas cylinders. In liquid form, it is usually transported through pipes or tanks (van der Zwaan et al., 2011). The choice of the delivery mode depends on the quantity and distance (Baufumé et al., 2013). Pipelines are the most cost- and energy-efficient way to distribute hydrogen as a gas over long distances (Liemberger et al., 2019; Messaoudani et al., 2016; van der Zwaan et al., 2011; Yang and Ogden, 2007). In a still immature market with moderate demand, tanks (on trucks or trains) are enough to accommodate the demand, and additional infrastructural planning is not needed (Baufumé et al.; Wietschel et al.; Yang and Ogden).

If the market and demand of hydrogen is higher or expected to increase, changes in the infrastructure need to be considered. Building new hydrogen pipelines has a cost range between 0.67\$/km/J and 7.4\$/km/J. In perspective, the cost of a natural gas pipeline ranges between 0.19\$/km/J and 0.75\$/km/J (Liemberger et al., 2019).

A hydrogen infrastructure can be realised by creating a new network, or by using an existing network, like the natural gas network. Regarding the development of a new infrastructure, various researchers have researched the development of an infrastructure to refuel hydrogen operating vehicles. van Benthem et al. (2006) studied the stimulation of private investments for hydrogen infrastructure in the mobility sector. They used the economic net present value approach for this. Markert et al. (2017) developed a technique that supports risk management and sustainability assessment for the development of a network of hydrogen refuelling stations. Stephens-Romero and Samuelsen (2009) presented a generic optimisation-based model which can be used to plan the strategic investments needed for hydrogen in the mobility sector. Other studies applied mixed-integer linear programming (MILP) to find the optimal hydrogen network (Mukherjee et al., 2015; Baufumé et al., 2013; Hugo et al., 2005; Kim and Moon, 2008; Kamarudin et al., 2009).

Apart from research that focuses on the fuelling stations of hydrogen vehicles, research has also been conducted on the development of a hydrogen infrastructure through Europe. Wietschel et al. (2006) developed two scenarios

with different shares of hydrogen are used and analysed the technical, economic and environmental aspects of these scenarios. Tzimas et al. (2007) calculated the required hydrogen infrastructure for Europe and determined how much this would cost.

Baufumé et al. (2013) pointed out the importance of using existing structures when rolling out new energy systems like hydrogen. Using an existing natural gas network can lead to a shorter and potentially cheaper transition. This does require changes to the existing natural gas network to enable the distribution of pure hydrogen. These changes can be traced back to the physicochemical differences in property between natural gas and hydrogen. The hydrogen molecule is lighter and has a lower molecular mass than natural gas and air, leading to 1.3 to 2.8 times more chance on leakage than with natural gas (Messaoudani et al., 2016). To prevent leakage, welding- and joining procedures of the pipes need to be improved (van der Zwaan et al., 2011). With these alterations, an already existing natural gas network can be considered as a good option to transport hydrogen.

Besides the molar mass, there are other differences in physical and chemical properties between natural gas and hydrogen. An overview of the essential features is provided in table 2.1. The caloric value by volume of natural gas, for instance, is higher compared to hydrogen. However, the heat capacity, caloric value by mass and the maximum flame temperature of hydrogen is higher compared to natural gas.

Properties	Hydrogen (H ₂)	Methane (CH ₄)	Unit
Molar mass	2.02	16.04	g/mol
Critical temperature	33.2	190.65	K
Critical pressure	13.15	45.4	Bar
Vapor density at normal boiling point	1.34	1.82	Kg/m ³
Vapor density (at T = 293.15 K and P = 1 bar)	0.0838	0.651	Kg/m ³
Specific heat capacity (at T = 293.15 K and P = constant)	14.4	2.21	KJ/kg/K
Specific heat ratio (C _p /C _v)	1.4	1.31	-
Lower calorific value by mass (lower heating value, weight basis)	120	48	MJ/kg
Lower calorific value by volume at 1 atm	11	35	MJ/m ³
Higher calorific value by mass	142	53	MJ/kg
Higher calorific value by volume at 1 Atm	13	39	MJ/m ³
Maximum flame temperature	1800	1495	K
Explosive (deniability) limits	18.2 - 58.9	5.7 - 14	Vol % in air
Limiting oxygen for combustion	5	12	Vol %
Flammability limits	4.1 - 74	5.3 - 15	Vol % in air
Auto-ignition temperature Laminar	560	600	C
Laminar burning velocity	3.1	0.4	m/s
Dilute gas viscosity at T = 299 K	9 × 10 ⁻⁶	11 × 10 ⁻⁶	Pa × s
Molecular diffusivity in air	6.1 × 10 ⁻⁵	1.6 × 10 ⁻⁵	m ² /s
Solubility in water	0.0016	0.025	kg/m ³

Table 2.1: Properties of hydrogen and natural gas (Messaoudani et al., 2016)

Apart from transforming the natural gas infrastructure to a pure hydrogen infrastructure immediately, it is also possible to inject hydrogen into the existing natural gas infrastructure and create a mixture. Different studies have been done to find an acceptable concentration of hydrogen in the natural gas network. [Haeseldonckx and D'haeseleer \(2007\)](#) for instance, found that it is possible to add hydrogen to gas until the mixture contains 17 vol% hydrogen. [Gondal \(2019\)](#) made a distinction between the transmission network, where the compressors are the limiting factor and only allow mixtures up to 10 vol% hydrogen, and the distribution network that allow mixtures up to 50 vol% hydrogen.

In gas mixtures, a difference of 2-5 vol% hydrogen, the difference in quality is a negligible quality difference ([Gondal, 2019](#); [Schiebahn et al., 2015](#)). The range where the end-use applications, like boilers, heaters and ovens need to be changed is between 20 and 50 vol% ([Gondal, 2019](#)).

Injecting hydrogen in the natural gas network under the 17 vol% makes it possible to have a constant hydrogen demand that does not require consumers to make the switch in end-user applications with additional investments. This could stimulate the development of hydrogen production projects. In the long run, this will obstruct the full roll-out of hydrogen to higher vol% as both investments in the natural gas network and end-user application will have to be made anyway ([van der Linde and van Leeuwen, 2019](#)). Creating a mixture between hydrogen and natural gas would therefore only postpone the infrastructural decisions that need to be made to have a fully running hydrogen economy.

2.2 NETWORKED INFRASTRUCTURES

Network infrastructures can be viewed as complex socio-technical systems ([Herder et al., 2008](#)) as they have physical subsystems and social subsystems ([Davis et al., 2010](#)). These infrastructures need to be accessible, affordable and reliable ([Davis et al., 2010](#)).

The physical subsystem describes the physical properties of a network consisting of nodes and edges ([Herder et al., 2008](#)). Energy networks are often not completed at once, but they tend to evolve and grow over time. The Dutch power grid consisted of several local networks that later merged into one national network. This national network in time has grown in capacity and geographic coverage ([Davis et al., 2010](#)). This evolutionary process of network development is characterised by:

- path-dependency,
- lock-ins,
- network effects and
- shared effort ([Chappin and Dijkema, 2008](#); [Davis et al., 2010](#); [Nikolic et al., 2008](#); [Xie and Levinson, 2009](#)).

Path-dependency is a concept that describes how certain historic choices cannot be undone, and that historic choice determines the possibilities of future choices (van Dam et al., 2013). Because of this, the characteristics of the current situation affect the conditions of the development of new transitions (Klitkou et al., 2015). If the situation is imperfect, this path dependency can lead to lock-ins. Lock-ins can be described as feedback of adapting to a specific technology (Klitkou et al., 2015). The concept network effect is defined as “a change in the benefit, or surplus, that an agent derives from a good when the number of other agents consuming the same kind of good changes” (Xie and Levinson, 2009). Lastly, a process of evolution is not singular; an evolutionary or revolutionary process is automatically a process of co-evolution, co-revolutions, making network evolution a shared effort (Nikolic and Dijkema, 2007).

The social subsystem of an energy network consists of all the different actors involved in the network who act according to their own needs, following their own strategies, own rules, own moral and cultural codes and who are governed by legislation and regulation (Herder et al., 2008). As the physical subsystems in the energy sector have evolved, the regulation and ownership of the social system have also undergone significant changes in the last years. For instance, the energy sector has been liberalised, from state-run to enterprise run (Davis et al., 2010).

Much research on network and network evolution has already been realised, leading to the understanding of how networks evolve, as well as the possibility to shape them (Chappin and Dijkema, 2008). Xie and Levinson (2009) have reviewed the progress of models regarding the growth of transportation networks. Cats et al. (2020) looked into the evolution of transportation networks in metropolitan areas and how they could serve as a model for the growth of these transportation networks as a function of cost and demand. Louf et al. (2013) have constructed a model that supplies building blocks that increase the understanding of the evolution of spatial networks and network properties. Herder et al. (2008) described how to design network infrastructures. Nikolic et al. (2008) have developed an approach for the modelling of infrastructure evolution and to a way to understand the decision-making process that is needed. Chappin and Dijkema (2008) created a framework to assess different designs for the transition of energy infrastructures.

The conducted literature search shows that a lot of research has focused on the evolution of infrastructures in the mobility sector, but the transition of energy infrastructures is relatively unexplored. Studies that have been performed in the energy domain, mainly focus on the design of these complex infrastructures and how to assess them. The transition from one infrastructure to another remains uncharted.

2.3 SYNTHESIS AND IDENTIFICATION OF THE KNOWLEDGE GAP

The literature review has concluded that the use of the existing infrastructure speeds up the transition to new energy sources like hydrogen. In previous research, the possibility of using the natural gas network for the distribution of hydrogen has been confirmed. Some adjustments are needed based on the difference in physical and chemical properties, considerable knowledge concerning the differences is already available. For this reason, the technical aspects of the transition will not be addressed in this thesis. There is a possibility to inject hydrogen in the natural gas grid; however, with this, the inevitable transition will only be delayed. Accordingly, the injection of hydrogen will not be considered in this research.

Much research that has examined the development of hydrogen infrastructure, focused on the development of fuel stations for hydrogen vehicles. A common approach for the development of a hydrogen infrastructure is the mixed-integer linear programming (MILP) optimisation of networks regarding various KPI's, such as costs. Factors that drive the development of hydrogen infrastructures have not yet been described in the literature.

Concerning the natural gas network and the future hydrogen network, these networks can be viewed as complex socio-technical systems where the evolutionary process is characterised by path-dependency, lock-ins, network effects and shared efforts. Research has been performed on how such network infrastructures evolve but as far as known to the author, no study has been completed regarding the transition of a new network based on an already established network.

This thesis will look into how a natural gas network transitions from fulfilling one purpose, the distributing of natural gas, to another, distributing of hydrogen while taking path dependency into account. As described in the introduction, the situation of this transition of the infrastructure has an additional complication as the natural gas network is still in operation, and that is not expected to change in the near future. This transition to a new network while fulfilling the demand of the existing network is novel. Gaining insight into how this can be done is crucial to plan an efficient transition. Therefore this research will focus on the effect of different strategies shaping the network transition.

3

RESEARCH FORMULATION

The previous chapter has uncovered the knowledge gap. This knowledge gap indicates that the transition from one infrastructure to another with a concomitant demand for both infrastructures is still unexplored in the literature. For this reason, this thesis focuses on how a new infrastructure based on and competing with an already established infrastructure transitions using different strategies.

3.1 RESEARCH QUESTION

This thesis focuses on the transition of the gas infrastructure to a hydrogen infrastructure and is centred around the main research question, which is formulated as followed:

How do different transition strategies for the transition of a natural gas infrastructure to a (partial) hydrogen infrastructure perform over time?

A common approach for the development of a new hydrogen infrastructure is by optimisation the whole network. With this method, the conditions and boundaries are defined. Within the option space, all possible settings are tried, and the desired outcome is determined using specified KPI's. With all settings being tested to find the optimum solution, no insight is acquired into any strategy that leads to this optimum and the process of finding the optimum can be seen as a black box. Although this is a useful approach for the development of a hydrogen infrastructure, in this thesis, a different approach is taken. In this research, a step for step approach is taken, optimising every current step locally without looking further ahead than the current time step. The decision to base the local optimisation on for this step for step approach is based on different strategies. This way, it is possible to get insight into the effect of strategies on the way the network transition will evolve while taking path dependency into account. The fact that with this approach path dependency contributes more to the development is also relevant. In the case of the hydrogen network, both the supply, demand and infrastructure are dependent on each other and therefore develop parallel to each other while interacting with each other. This does not mean that optimising the whole system at once is now irrelevant. However, when looking at the general principle of the transition of new infrastructure based on and competing with an already established infrastructure, then it is insightful to have an understanding of the system where path dependency does play a significant role, and where a generic optimisation does not neutralise this path dependency.

3.2 RESEARCH METHODOLOGY

The chosen approach to tackle this issue is the modeling approach. Herder et al. (2008) have indicated that infrastructures can be viewed as complex socio-technical systems with physical and social subsystems. (Davis et al., 2010). The modelling approach is an appropriate methodology to study these complex socio-technical systems because new theories, concepts and knowledge about the processes happening in the complex system can be analysed (Albino et al., 2006).

The modelling approach distinguishes itself by being explorative for various policy measures and different scenarios can be introduced. This research question aims to understand how the transition from a natural gas grid to a hydrogen grid evolves and how this transition can be influenced by different strategies. Hence, the modelling approach is appropriate.

This modelling approach is applied in Netlogo where an agent-based model is constructed. The benefit of Netlogo is that it is possible to program rule-based. The natural gas network can be viewed as a dynamic graph with elements that changes in time under previously specified rules. The discrete-time steps used by Netlogo make it possible to include the element of path dependency where the current situation is used as a base for the decision space, which is further determined by the predetermined rules. The model itself is not a typical agent-based model as no real agents are included in the model. The edges and nodes, however, are 'made smart', and these *agent* drive the transition process of the network.

The advantage of using the modelling approach is that emerging patterns can be observed ex-ante, and an understanding of the transition process can be obtained. However, there is also a limitation to the modelling approach. To construct a model in the timeframe of this master thesis, many assumptions and simplifications have to be made. In doing so, it is possible to discover emerging patterns and trends as a result of specific strategies, however, the results are not accurate. Therefore, it will not be possible to make accurate predictions of the outcome of various strategies. However, the purpose of this research is to evaluate the effect of strategies on a system level, and this is possible.

Concerning other research approaches; the design research approach looks into the development of an application, institution, process or service in a structured way in order to solve a void in a socio-technical system. This research does not aim to design the new infrastructure but intends to use the already established processes of the network to uncover how a transition of such an infrastructure can take place and how this adaption can be influenced with different strategies.

With regard to the qualitative research approach, there is not a situation where this process of infrastructure adaption has already been implemented, and there is no theory describing it.

A quantitative research approach is not possible in the context of this thesis.

Infrastructure projects are large, take time to realise and are cost intensive. No pilots have been done, and there is no data available yet on this transition process.

3.3 SUB-QUESTIONS AND THEIR RESEARCH METHODS

The main research question is broken down in four sub-questions that are formulated as followed:

3.3.1 Sub question 1: How should, based on graph-theoretical concepts, the transition from natural gas to hydrogen infrastructure, based on different strategies, be represented?

This question aims to provide a way the infrastructures should be represented to allow the modelling approach. This means that a topology of the network should be found based on graph theoretical concepts and that transition paths and strategies need to be identified.

In regard to the representation, following the graph theoretic concepts, a network consists of nodes and edges. When considering an infrastructure, nodes can represent; intersections of the infrastructure, supply points for both hydrogen and or natural gas and demand natural gas and/or hydrogen. The edges are the transmission paths for both hydrogen and natural gas. Transmission can occur in different ways (e.g. pipe or tanks). It needs to be determined if the network with the edges and nodes is based on an actual network or on a theoretical topological network. Additionally, different strategies are identified that drive the adaption from a natural gas infrastructure to a hydrogen infrastructure.

To get input on the first part of sub question 1, information needs to be gathered on the properties of the natural gas network, and concepts of graph theory need to be attained. When making the translation from a natural gas infrastructure to a graph, assumptions and decisions regarding properties are made. These decisions might influence the relevance of the model with regard to reality. Considerations need to be made, and all assumptions will be documented.

3.3.2 Sub question 2: How should a conceptual model of the transition of a hydrogen infrastructure, based on an already established natural gas infrastructure, be made?

This second question aims to translate the system description that was developed in the first sub-question into a conceptual model. The conceptional model makes it possible to make a layout of the different transition steps, the processes driving the transition and the behaviour of the actors. An interpretation of the network representation is provided here. The conceptual model is the bases for the computer model. Further abstractions and

assumptions need to be made, and the conceptual model helps to formulate these and to make these assumptions explicit.

Aspects that are covered, are the identification of the actors, their specific drivers, the processes that drive the system behaviour and the different key performance indicators (KPI's) upon which the strategies are evaluated. A Business Process Model and Notation (BPMN) diagram will be used to show how the different aspects of the model interact.

3.3.3 Sub question 3: What is the effect of transition strategies for the transition path towards a hydrogen infrastructure?

This question aims to explore how the transition of the natural gas grid to a hydrogen is influenced by strategies. In order to research these effects, the conceptual model is implemented in NetLogo. The choice for Netlogo is made because it is possible to model in a rule-based manner. When this is realised, different strategies can be applied in the model. By using different strategies, different outcomes are obtained. These different outcomes are the basis for evaluating the effect of different strategies.

NetLogo as modelling environment is chosen because of its ease of use, which is preferable as this thesis needs to be completed in a relatively short period of time (van Dam et al., 2013). The limitation of NetLogo is that the model cannot become too complex because the programming language only allows simple data structure. However, for the purpose of seeing the effect of the strategies on the evolution, NetLogo suffices. The outcomes of the different strategies of the model and the sensitivity analysis are processed in python.

3.3.4 Sub question 4: How can the insights on system-level be used and interpreted to understand the transition to a hydrogen infrastructure?

This last question aims to understand the outcomes of the model in order to apply the insights for the actual transition of the infrastructure, which is needed for the Netherlands to reach their environmental goals. With a better understanding of the effect of different strategies, policymakers can learn and draw conclusions and understand the implications of various strategies and make informed choices.

In order to be able to use these lessons, the insights on system level should be translated into comprehensive strategies that can be applied to the Dutch network. The results are coupled to network metrics in order to explore the relation between the effectiveness of a strategy and the characteristics of the starting point of the network.

4

SYSTEM IDENTIFICATION AND SYSTEM DECOMPOSITION

In this chapter, a valid representation of the natural gas infrastructure, that will be used as input for the transition from a natural gas to a hydrogen infrastructure, is explored. In order to formulate a valid representation, first the Dutch gas network, which can be seen as a complex socio-technical system, is described. Then gas infrastructures in some other countries are described to find similarities and differences compared to the Dutch network. This way, a representation can be chosen that could be applicable in more countries than the Netherlands. After getting a better understanding of this socio-technical system, the transition dilemma is described. This dilemma often arises when investments are required for the transition and at the same time to make the transition work, simultaneous investments need to be made by other actors. Consequently, the network transition can only work if the end-user appliance transition is done at the same time. If one actor delays, it will delay everything according.

Subsequently, more information on gas topologies is given before ending with describing the chosen representation in this study.

4.1 THE DUTCH INFRASTRUCTURE

This section describes the Dutch gas system. This system includes the physical system, being the pipelines and the social system, being the actors.

4.1.1 The technical system

The natural gas infrastructure in the Netherlands consists of pipes and stations. In the gas infrastructure, a distinction is made between the transmission network and a regional distribution network. In the Netherlands, the transmission network is laid double, making it possible to transport two different qualities of natural gas; gas with a high Wobbe index, high-calorific gas and gas with a lower Wobbe index, low-calorific gas extracted from the Groningen field ([Gasunie, 2015](#)). Different types of stations are incorporated in the natural gas network. These are mixing stations, where the quality of the gas is checked, and the correct mixture is confirmed, compressor stations where the pressure in the pipelines can be maintained, and pressure stations where the pressure of gas from the main transmission network is decreased in order to be fed into the distribution network ([Ministerie van Economische Zaken, 2017](#)). The Netherlands imports and exports gas and a significant part of the gas that is transported through the network is not for Dutch use. In 2017, 40 billion m³ of gas was imported and 54 billion m³ of gas was

exported (Gasunie, 2015).

Figure 4.1 shows the current transmission network where the yellow lines represent the gas with the high-calorific, and the grey lines represent the low calorific gas extracted from the Groningen field. Entry- and exit points are indicated with respectively the grey circles and the grey triangles. The mixing stations, the compressor stations and the pressure stations are respectively indicated as grey circles with a grey dot in the middle, the grey circles with white middle and the white circles.

In figure 4.2 the transmission network and the regional distribution network is presented. Here the green lines are the distribution network. The total length of the transmission network is 5330 km (Gasunie, a) and the length of the distribution network is 5926 km (Gasunie, a).

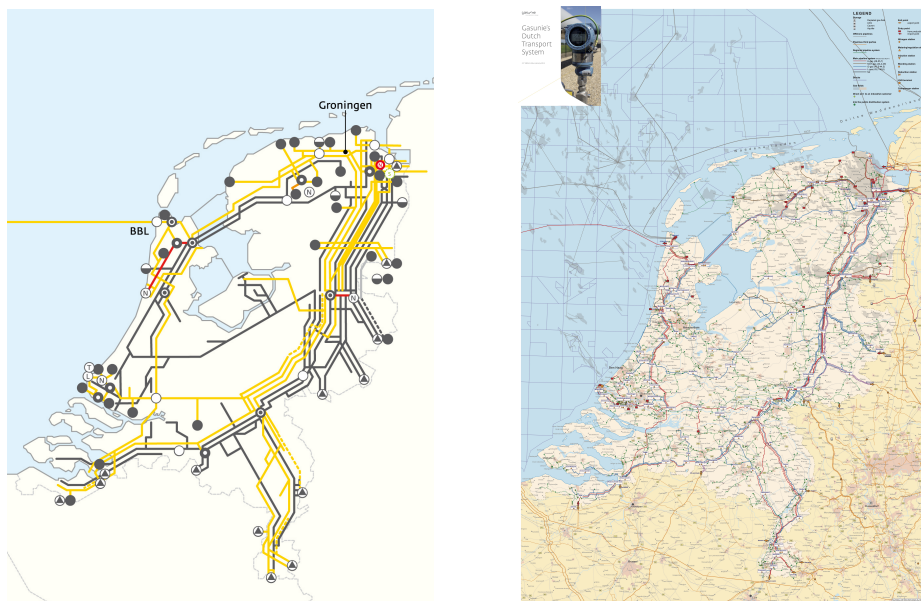


Figure 4.1: Main transmission network Figure 4.2: Transmission and distribution network

Similar to the natural gas infrastructure, a hydrogen infrastructure would consist of a high-pressure transmission pipeline network and medium and low-pressure distribution pipeline network. The distribution network delivers hydrogen to the end-users (Tzimas et al., 2007). An additional form of transport is a fleet of trucks that can deliver hydrogen when it is liquified (Tzimas et al., 2007).

The caloric value by volume of hydrogen is around 13MJ/m³, while the caloric value of natural gas is 39 MJ/m³. In order to have the same amount of energy, three times the amount of hydrogen needs to be delivered compared to natural gas. This increase in required volume can be realised by tripling the pressure.

On average a new pipeline costs €2005 per meter Tzimas et al. (2007). It is also possible to use natural gas pipelines for the transport of hydrogen. However, there are additional costs adapting the current natural gas network

to a hydrogen network, extra compressors are needed and to prevent leakage, better welding techniques and joining procedures are required (van der Zwaan et al., 2011). The costs for adaption are not made specific in the literature. However, it is indicated that these costs are minor when compared to the costs of a completely new infrastructure (Stedin and Kiwa, 2019) and are more likely to be in the magnitude of hundreds of euros instead of thousands of euros (TNO). van Wijk and Hellinga (2018) indicates that the costs for changing the infrastructure would be in the order of 5% to 10% of the costs of constructing a new infrastructure.

4.1.2 Actors involved in the natural gas and hydrogen system

The actors that are involved in the infrastructure adaption can be clustered in the actors that consume hydrogen and or natural gas, the actors who produce the gasses and the network operators. Regarding the consumers, natural gas is mainly used in the heavy industry to generate heat and where it is used as feedstock, in the mobility sector to power fuel cell vehicles, in the power plants to generate electricity and in the built environment to deliver heat.

In the **industry sector**, both hydrogen and natural gas are currently used. Currently, hydrogen is mainly used as feedstock. In the Netherlands, almost 50% hydrogen is applied in refineries, and 32% hydrogen is used for the production of ammonia (Ministerie van Economische Zaken, 2017). However, there is also a significant potential for hydrogen as a way to create carbon-free heat needed for industry processes (van der Linde and van Leeuwen, 2019). In the Netherlands around 10 billion m³ natural gas is used in the industry sector (Blok, 2015), this sector has a potential demand of 34 billion m³ of hydrogen. This hydrogen demand can be divided in 6 billion m³ for feedstock and 28 billion m³ for high-temperature industry processes (Ministerie van Economische Zaken, 2017). Based on figure 4.2, there are approximately 330 direct exit points for industrial customers.

Considering that hydrogen is already used in this sector, big wins in regard to the reduction of carbon emissions can be achieved by expanding the usage and replacing grey hydrogen by green or blue hydrogen. Currently there are studies looking into the more hydrogen applications in the industry (Gigler and Weeda, 2018; Weeda and van Hout, 2017). These two studies have been commissioned by the Ministry of Economic Affairs & Climate and by the Gasunie. Not only (semi) governmental parties are interested in this topic, also the port of Rotterdam is looking into ways to become carbon-free. Samadi et al. (2016) have drafted different plans for the Port of Rotterdam where sustainably produced hydrogen plays a big role. However, at the moment, there are no concrete and large-scale implementation plans ongoing.

The utilisation of natural gas in the **built environment** should become obsolete, and new construction projects are realised without natural gas connections. For the already established buildings, alternatives to natural gas are sought and implemented. In some cases, hydrogen is the optimal al-

ternative. 10,5 billion m³ natural gas is used in the built environment (Blok, 2015), and this is expected to only decrease to 9 billion m³ hydrogen. (Ministerie van Economische Zaken, 2017). There are a variety of alternatives to replace natural gas, and some of these alternatives are already implemented on a small scale. It can be expected that the start of phasing out of gas in the built environment will start shortly.

In the **mobility sector**, various options are considered and implemented to make this sector carbon-free. The two main contenders are battery electric vehicles (BEV) and fuel cell vehicles that run on hydrogen (FCEV). In the Netherlands, the usage of BEV has advanced the most. One reason for this is that the electricity infrastructure in the Netherlands is extensive and it can be used with minimal additional resources when expanding the usage of BEV's. In the long run, it is not clear whether BEV's are preferable over FCEV cars because a high number of BEV's could be too demanding for the current electricity grid, meaning an upgrade of the electricity grid would be needed and that is anticipated to be very expensive.

1 billion m³ of natural gas is used in the mobility sector (Blok, 2015), the potential of hydrogen exceeds the substitution of this natural gas demand. An estimate of the hydrogen potential in the mobility sector is up to 11 billion m³ (Ministerie van Economische Zaken, 2017).

Both the mobility sector and the built environment are supplied through the distribution network. There are 1100 stations where the natural gas is converted from the transmission network to the distribution network (?)

In the Dutch **electricity sector**, 60% of the electricity is generated through thermic sources, one of which is natural gas. 13 billion m³ of natural gas is used for the Dutch electricity generation (Ministerie van Economische Zaken, 2017) and there are 36 natural gas-fired power plants in the Netherlands (Entsoe). Hydrogen can fulfil a vital system role in the electricity generation in addition to other carbon-free energy sources like sun and wind energy. Peaks in wind energy generation can be used to produce sustainable hydrogen. If the thermal power plants are closed, the electricity production is less stable and controllable. Hydrogen can provide a possibility to overcome this problem as hydrogen can be stored and used when needed. Potentially 11 billion m³ of hydrogen will be used to generate electricity (Blok, 2015). Different institutions are researching how natural gas-fired power plants can be configured to burn other gasses such as hydrogen. Wärtsilä, a Finnish power plant production company for instance, has developed a technique that makes the adaption possible (Seijlhouwer, 2020). In the Netherlands there are also concrete plans to adapt the natural gas-fired plants to burn hydrogen instead of natural gas. The Magnum plant in the north of the Netherlands for instance wants 1/3 of its capacity to generate electricity with hydrogen by 2023, and by 2030 it should be a fully functional hydrogen power plant (Gasunie, o).

The biggest share of the **natural gas production** in the Netherlands comes from the Groningen field. In 2015 the Groningen field produced 45 billion

m³ (Blok, 2015). Gas imports were 40 billion m³, and the gas exports were 54 billion m³ (CBS, 2017). There are 27 points where the natural gas enters the network, as can be seen in figure 4.2.

The global **production of hydrogen** is almost entirely based on fossil fuels. Consequently, hydrogen is responsible for around 830 million tons of CO₂ per year (IEA). 50% of the global hydrogen demand is produced through steam reforming of natural gas (Dincer, 2012). In other cases, hydrogen can be generated from oil/ naphtha reforming from refineries or coal gasification. These two methods account for respectively 30% and 18% of the hydrogen production (Dincer, 2012). The annual hydrogen production in the Netherlands is around 10 billion m³ hydrogen. The largest share is produced in the area of Rotterdam (6,1 billion m³), followed by Geleen (1,8 billion m³), Delfzijl (1,3 billion m³) and IJmuiden (1,0 billion m³) (Ministerie van Economische Zaken, 2017). With this production capacity, the Netherlands is the second largest hydrogen producer of Europe (Ministerie van Economische Zaken, 2017).

If hydrogen is produced while emitting CO₂, it is referred to as grey hydrogen. It is however also possible to capture, store and even use the carbon emissions that are produced. If hydrogen is produced with carbon capture and storage, it is referred to as blue hydrogen. However, this last technology is still expensive and is not yet applied on a large scale (TNO).

Hydrogen can also be produced using electricity, when electricity is used to drive the electrolysis process, which splits water into hydrogen and oxygen (Clark and Rifkin, 2006). Currently, only 3.9% of the global hydrogen production is created through electrolysis (Dincer, 2012). If the electricity used for the production of hydrogen originates from renewable sources of energy, such as solar photovoltaic (PV), wind, hydropower or geothermal energy, the hydrogen is referred to as green hydrogen (Clark and Rifkin, 2006).

There are big plans to scale up green hydrogen production in the future. By 2030, the Netherlands wants to produce 3 billion m³ hydrogen sustainably in the northern part of the Netherlands (Ministerie van Economische Zaken, 2017) and there are plans for three green hydrogen production sites (Leguijt et al., 2018). Large offshore wind farms are under construction, and the current installed wind capacity in the Netherlands will be increased with 167% by 2025 (RVO). This renewable energy can be used to produce green hydrogen and at the same time could mitigate the challenges in dealing with excess wind energy.

Gasunie is the **system operator** and owner of the main transmission network. The district system operators maintain the distribution network. There are seven different district system operators in the Netherlands. In 2000 the system was unbundled and with this separating the production and sales from the transmission and distribution. The system operators are natural monopolies and are regulated in terms of the profit they can make.

An overview of the expected hydrogen and natural gas generation and production can be found in table 4.1. The numbers in this table are based on the data of Ministerie van Economische Zaken (2017), Blok (2015) and CBS (2017). The disbalance between the generation and consumption of hy-

	Natural gas (billion m ³)	Hydrogen (billion m ³)
Generation		
Import	40	-
Own gas extraction	59	-
Grey hydrogen production	-	10
Blue hydrogen production	-	0
Green hydrogen production	-	3
Total	99	13
Consumption		
Industry	10	24
Built environment	10,5	9
Mobility	1	11
Electricity generation	13	11
Other	10	-
Export	54	-
Total	98,5	55

Table 4.1: Hydrogen and natural gas generation and consumption

drogen can be traced back to the fact that these numbers are based on two different sources and indicate different things. In the case of generation, the current installed capacity and the current confirmed plans for generation are included, while the consumption renders the potential for hydrogen in a specific sector.

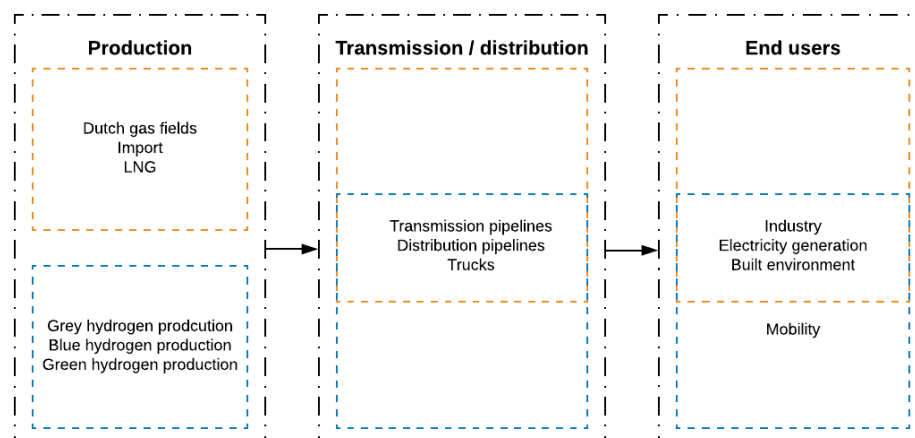


Figure 4.4: Adjusted supply chain of natural gas and hydrogen in the Netherlands

When comparing the supply chain of hydrogen and natural gas, the production and production sites are different. Nevertheless, the transmission of both gasses is similar. With regard to the end-users, the end-use applications need to be adjusted or changed to the physicochemical properties of the gas used.

In fact, hydrogen can be used in all sectors, especially in the industrial sector, the electricity generation, in the built environment but also in the

mobility sector. With this, hydrogen can replace natural gas. A schematic overview of the supply chain and the applicability to either hydrogen or natural gas is displayed in figure 4.4.

4.2 INTERNATIONAL GAS NETWORKS

The natural gas consumption worldwide is extensive, and it is the second-largest energy source worldwide. In 2019, 3930 bcm (billion cubic metres) was consumed, and natural gas accounts for 23,9% of the energy consumption worldwide (BP, 2019). With this extensive gas consumption, most countries have an infrastructure to enable the application of natural gas. In this paragraph, three examples of gas infrastructures in countries other than the Netherlands are given and compared to the gas infrastructure in the Netherlands. The comparison makes it possible to research the general properties of gas infrastructures in countries by looking at similarities and differences. This makes it possible to create a representation of the infrastructure that is more generic, making it possible for the findings of this thesis to be applied in a bigger context.

4.2.1 Gas infrastructure in the United States of America

The gas infrastructure in the United States is approximately 483.000 km. There are 1400 interconnection points where the pipelines meet, and the infrastructure can be divided into 24 market hubs (Business Roundtable). The gas network of the United States can be viewed in figure 4.5. A large part

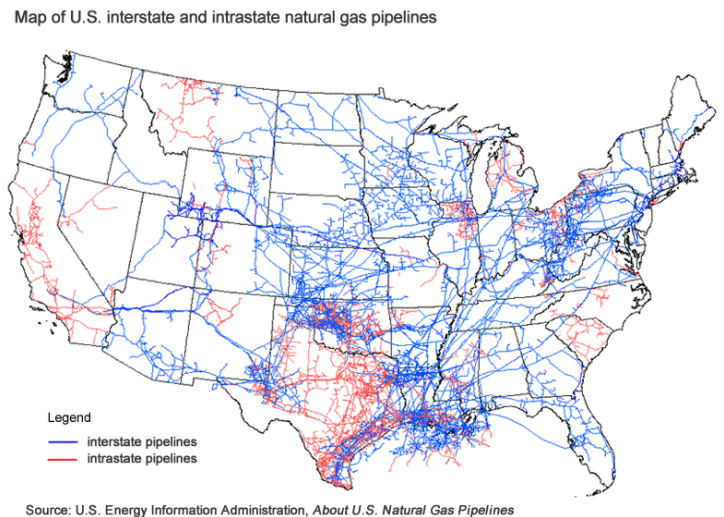


Figure 4.5: The American gas infrastructure

of the natural gas import comes from Canada. Since the extraction of shale gas has become feasible, the internal shale gas production in the USA has increased significantly. The shale gas is transported through the already established pipelines. The gathering systems and distribution systems mainly

consist of smaller low-pressure pipelines (U.S. Energy Information Administration). The pipelines that cross state boundaries have a larger diameter and have a higher pressure (U.S. Energy Information Administration). There are local distribution companies that are responsible for the delivery of gas to end customers (U.S. Energy Information Administration).

4.2.2 Gas infrastructure in the United Kingdom

The national gas transmission network in the UK is 7600 km (Dodds and McDowall, 2013). Next to the transmission network, there are eight regional distribution network where the gas is transported in pipes with a smaller diameter and under lower pressure. These distribution network together have a total length of 280,000 km. The transmission network is shown in figure 4.6.

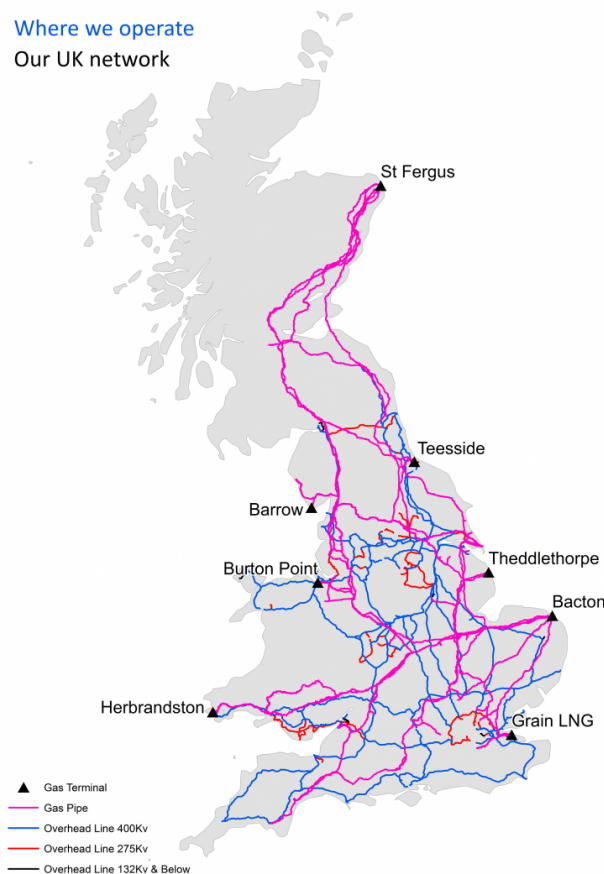


Figure 4.6: The gas infrastructure in the UK

Generally, consumers are connected to the distribution network. However, some large consumers like power plants and industry sites are directly supplied from the transmission network. The system operators are regulated natural monopolists (Dodds and McDowall, 2013). The consumers of natural gas can be divided into four sectors; those who generate electricity, industry, domestic uses and others (entailing government use, commercial use, agriculture etc.) (Dodds and McDowall, 2013).

The UK's climate goals also push towards the transition of the natural gas

network and the country is investigating whether a change of (a part of) the network is needed to reach the climate goals (Dodds and McDowall, 2013).

4.2.3 Gas infrastructure in Belgium

The Belgium gas network also has a transmission network and a distribution network. The transmission network consists of 3817 km of pipes, and the distribution network has a total length of 60000 km (Synergrid). Figure 4.7 displays the Belgium transmission network.

The distribution network is divided into 17 different regions, each having its own DSO.

Most customers are supplied through the distribution network. The different sectors that use natural gas are the built environment, industries and electricity plants. 230 industrial sites and natural gas-fired power stations are connected to the network (Fluxys).



Figure 4.7: The Belgium gas infrastructure

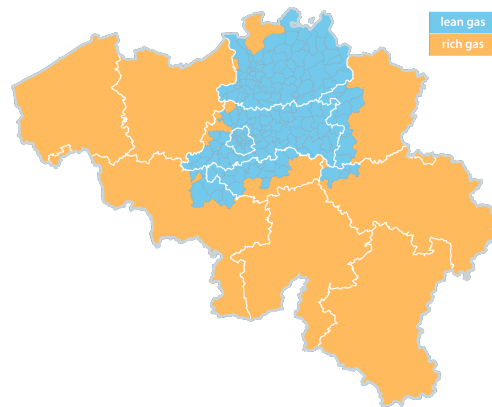


Figure 4.8: Regions in Belgium with either high-calorific gas or low-calorific gas

A particular aspect of the Belgium natural gas network is that there are two separate active networks; one network that transports high-calorific gas and one that transports low-calorific gas. These two networks do not operate beside each other in the same region, but separate regions have their own network. This can be seen in figure 4.8.

The low-calorific natural gas comes from the Groningen field, and as the Netherlands plans to phase out the production of this field, there are plans to switch the end-users of the low-calorific natural gas to use high-calorific natural gas. This should be finalised in 2029.

4.2.4 Comparison to the Dutch network

In the comparison between how the natural gas infrastructure is set up in the United States, the United Kingdom, Belgium and the Netherlands, many similarities can be observed. All countries have a (high pressure) transmission network which branches out into different distribution networks. Gas is delivered to smaller customers through the distribution network. In some

cases, larger customers such as industrial consumers or electricity plants, are directly connected to the transmission network. The European countries are looking into ways to implement hydrogen as an energy source to reduce their carbon footprint. For the distribution of hydrogen, the transition of the current natural gas network is considered as a good option.

The aspect that distinguishes the Dutch network from the other networks is the double transmission network allowing the transportation of two different types of gas next to each other.

4.3 THE TRANSITION DILEMMA IN THE INFRASTRUCTURE

Substantial investment are needed for the transition of networks (Dunn, 2009). However, investments are only made if there is an assurance that the investments are not in vain. This leads to a dilemma. This dilemma is described to give more insight into the interaction between the different actors involved and how their interaction can influence the evolution of the hydrogen network.

The fact that the current natural gas infrastructure can serve as a basis for a new hydrogen infrastructure reduces this dilemma as the investment costs are reduced (Lowesmith and Hankinson, 2006). The cost for the adaption of gas infrastructures are still considerable, and therefore the transition dilemma is not entirely diminished.

Investors in the infrastructure need enough assurance for demand from consumers before they invest in a new infrastructure. Consumers need enough assurance that the new infrastructure will come through before investing in new, or changing their current applications. Good collaboration between the different actors involved is therefore needed to assure the development of a new infrastructure (Moran and Wiltraut, 2015). Gasunie, the Transmission system operator in the Netherlands has indicated that they want to take up an active role and try to reduce this transition dilemma (Institute for sustainable process technology, 2020). However, Gasunie also indicates that bottom-up initiatives coming from the industries and other consumers are needed as well (Institute for sustainable process technology, 2020). From the bottom side, investments need to be made to overcome the different properties of natural gas and hydrogen. Mutual assurance and trust concerning the TSO to deliver the infrastructure, and the consumers that will use the new infrastructure to foresee in their energy demand, is needed for both parties to both invest in the new energy system, in this case hydrogen.

4.4 GAS TOPOLOGIES

The topology of a network describes how nodes and the connections between the nodes are organised (DNS). It is not uncommon to represent a gas network as a graph. This representation is for instance made in research that analyses the effect of a failure in one part of the network on the network as a

whole(Ouyang and Dueñas-Osorio, 2011). Another study shows the security of supply of an international gas network (Praks et al., 2015) and researches the reliability of a gas network (Praks and Kopustinskas, 2014). Depending on the objective of the study, the representation, accuracy , and level of abstraction can vary.

In all three reviewed researches, nodes are classified into at least two different types; source nodes and sink nodes. Gas is inserted into the network through the source nodes. Ouyang and Dueñas-Osorio (2011) In the research of Ouyang and Dueñas-Osorio (2011), an additional node is also added; transmission nodes that serve as a connection point. In some studies, compressor stations are also added in the representation (Ouyang and Dueñas-Osorio, 2011; Praks et al., 2015).

The edges represent the pipelines. In the representation of the gas network by Ouyang and Dueñas-Osorio (2011), a distinction is made between the gathering system where the natural gas is transported towards a processing plant, the transmission system where the gas is transported from these processing plants and the distribution system where the gas is delivered to the customers. This distribution system has a more extensive network with more branches. The representation of Praks et al. (2015) takes the capacity of different parts of the network into account and indicates that some pipelines are unidirectional. The representation of Praks and Kopustinskas (2014) also includes both the capacity and diameter of the pipelines.

In the broadest sense, the network consists of nodes and edges between the nodes. Centrality measures can be used to determine the relative significance of nodes within the network (Yang, 2013). There are various centrality measures that determine the importance of the node based on different criteria. According to Giustolisi et al. (2019), the most suitable centrality metrics for spatial networks are the betweenness centrality, closeness centrality and degree centrality. These describe the number of times a node is on the shortest path between every other two nodes in the network; the distance the node is located to other nodes in the network, and the number of links the node has as a percentage of the possible connections a node can have.

4.5 REPRESENTATION OF THIS STUDY

This research focuses on the transition of the natural gas infrastructure to a (partial) hydrogen infrastructure. An adequate representation of the natural gas and hydrogen network needs to be made that depicts the essences of the transition of the infrastructure. The essence of the evolution can be found in the different (potential) consumers of either natural gas and or hydrogen with or without the ability to switch from natural gas to hydrogen. Additionally, a choice needs to be made which fragment of the infrastructure to change at which moment.

4.5.1 The system description

In the representation of the system, the different consumers of natural gas and hydrogen are represented as distinct entities with different characteristics. The entry points where both the natural gas and the hydrogen enter the system, can be represented as source nodes. Sink nodes represent the demand points where the gas is extracted from the network. The Dutch national gas network consists of mixing, compressor and pressure stations. For the interest of simplicity, while securing the essence of the infrastructure transition, such stations are left out of this representation as they do not influence the transition progress. Transmission nodes, as described by [Ouyang and Dueñas-Osorio \(2011\)](#), are included in the representation of the infrastructure for this thesis. These nodes can serve as a base from where pipelines – edges – can be constructed. In the chosen Representation in this thesis, only the already existing node will be used, and option to add new nodes are not considered.

The edges in the system, similar to previous studies, represent the pipelines. These can be both hydrogen and natural gas pipelines or a connection in the form of a tank that supplies the connecting nodes with the needed natural gas or hydrogen. Regarding the capacity, [Gasunie and TenneT \(2019\)](#) indicated that the current natural gas network has enough capacity to fulfil the new tasks of transporting hydrogen in the new energy system. For this reason, the assumption is made that the capacity of the current infrastructure is not a constraint in the system and that all the hydrogen and the natural gas that is entered in the system through the entry points, can be transported. The direction of the gas flow is not considered.

Although at first the representation and topology of the system is not based on a specific topology of an existing gas network, different arrangements of nodes and edges will influence the strategies chosen. This makes it is possible to analyse whether the effect of a specific strategy is general or dependent on the arbitrary arrangements. For further analysis, a representation of the Dutch low calorific gas network, the network of the United Kingdom and Belgium are constructed in order to test the effect of the strategies in the situation in the Netherlands, Belgium and United Kingdom.

The distinctive aspect of the Dutch natural gas network having a significant part of the main transmission network laid out double to enable the transmission of different qualities of gas, is not incorporated. The reason for the exclusion of the double laid network is twofold; with a starting point of a single network, a better understanding of the transition principles can be uncovered. Second, as the situation of the double main transmission network in the Netherlands is unique, it would limit the usability of the results beyond the Netherlands [4.2](#).

Additionally, the possibility of injecting hydrogen in the natural gas network is not included in the representation. As described in section [2.1](#), the injection of hydrogen would only postpone the transition to a pure hydrogen

network.

The distribution network is not represented as a sub networked and branched out infrastructure, but instead, it is represented as a sink node where the gas leaves the transmission network. The reason for not representing the full distribution network is because it is a pervasive network, and the addition of this distribution network does not add insight into the transition of the main infrastructure. In regard to the different type of nodes; hydrogen source nodes, natural gas source nodes, export sink nodes, industrial sink nodes, electricity plant sink nodes, mobility sink nodes and build environment sink nodes, generally only the last two nodes are connected to the distribution network, and the other nodes are often directly connected to the transmission network. Presenting how the built environment and mobility sector are connected to the distribution network, is disproportionate to the increased complexity of including the distribution network. The distribution network also needs to be changed to a hydrogen network, but this process is different from the transition of the transmission network. The focus of this thesis is on a higher aggregation level. For this reason, the mobility sink nodes and built environment sink nodes are combined as one demand node where the main transmission network would otherwise branch out to the distribution network. The demand of these sink nodes reflects on the proportion of the mobility sector and the built environment. The total length of the distribution network however is included in the representation.

4.5.2 Adaption possibilities

The current natural gas network needs to be transitioned to a (partial) hydrogen network. This transition is both technical as topological. The technological changes deal with the change caused by the difference in physicochemical properties between hydrogen and natural gas. The topological changes describe the changes of the connections between the nodes. This latter is the focus of this thesis.

The changes to the topology concern both nodes and edges. A node can switch from the demand of natural gas to the demand for hydrogen. The changes to the edges can be:

- Changing the type of gas that runs through the pipeline,
- Adding a new pipeline for either natural gas or hydrogen or
- Adding a (temporary) edge in the form of a truck connection that delivers either natural gas or hydrogen from one node to another.

4.5.3 Strategies

Different strategies can be executed to simulate the adaption of the natural gas network. The strategies are shaped by four tactical options that determine the strategy option space. One strategy is the combination of the settings

formed by the four different tactical options.

The first tactical decision comprises of several options that can be considered. Whenever there is a budget available, and there are multiple changes possible, a choice between the options needs to be made. This choice is optimised locally. It can be based on:

- The option with the lowest costs,
- The options with the highest contribution to one of the neighbouring nodes,
- The option with the highest contribution to all the adjacent nodes,
- The option where the contribution divided by the costs is the highest,
- A mixture of these options through time.

The second tactic regards whether or not to prioritise the export and import pathways of both natural gas and hydrogen. The Netherlands, with its location, is currently a hub for the flow of natural gas and a big part of the gas that flows through the Dutch system, is transit gas. The Netherlands is seen as a 'natural gas roundabout', and it has the ambition to extend this role to hydrogen as well. This strategy aims to investigate what this ambition will do to the system when priority is given to those trajectories that connect the import and export points for both hydrogen and natural gas.

The third tactic concerns the choice to construct new network sections or only work with the existing network while transitioning the existing network trajectories from gas to hydrogen. This tactic aims to investigate how the network will evolve based on the existing network only, or how and if new pipelines are needed for the development. The construction of new pipes makes the process more costly than using only the current pipelines. However, can supply of sufficient natural gas and hydrogen be guaranteed during the transition? When the choice is made to construct new pipelines, this can be based on intensively used truck connections or on connections where there is a high need for a new connection. It is also possible to allow both options for the construction of new pipes.

The last tactic concerns the way the budget is allocated over time. This can either be constant, increasing or decreasing over time. The total sum of the money allocated will be the same in all settings.

4.6 SUMMERY CHAPTER 4

In this chapter, the first sub-question is answered. First, the Dutch natural gas system is described by discussing the technical system and the social subsystem. The Dutch gas infrastructure consists of a transmission network that transport natural gas under high pressure over long distances, and an extensive distribution network that delivered the natural gas to customers.

Additionally, two different qualities of gas are available in the Netherlands, high calorific gas and low calorific gas. These gasses are transported separately.

The different actors involved can be categorised in actors involved in the production or generation of gas, the consumers of gas and the system operator. Consumers can be grouped in four main sectors, industrial consumers, electricity plants, the built and the mobility sector.

In comparison to gas infrastructures in other countries, having two separate gas infrastructures for two different gas qualities is unique. The transportation of gas through high-pressure transmission networks and medium and low-pressure distribution networks however is conventional.

For new infrastructures where investments by end-users are needed, a dilemma arises between them and the parties responsible for the infrastructure. Mutual trust and assurances are needed to overcome the barrier to invest.

Representing gas infrastructures and graphs is not uncommon in the literature. Three different studies were reviewed in these researches. The supply and demand actors in the system are represented by source- and sink nodes. Pipelines are represented by edges.

The accumulated information on gas infrastructures and graphs makes it possible to develop a representation that is used in this thesis. Source nodes represent the natural gas and hydrogen production sites. Three different clusters of demand-side customers are defined and represented by sink nodes; industrial customers, electricity plans and customers connected through the distribution network. This last cluster represents both the built and the mobility sector. The distribution network is not included in this representation.

An edge can either be a natural gas pipeline, a hydrogen pipeline or and temporary tank connection.

The arrangement of the nodes and the edges between them, the topology, is random. The distinctive aspect of the Dutch natural network; the two separate gas infrastructures alongside, is not included in the representation.

The network can transition by allowing a natural gas network to be changed to a hydrogen network, by activating a temporary tank connection or by constructing a new pipeline. The transition of the network is evaluated with regard to the effect of different strategies that are constructed based on the effect of tactical decisions. The first tactic looks into the prioritisation of the change of the network when there are multiple changes possible. The second tactic looks into the prioritisation of the export of hydrogen and natural gas. The third tactical option evaluates the option of constructing new networks, and the fourth tactical option explores the possibility to allocate the budget differently over time.

5 | CONCEPTUALISATION

A representation of the natural gas network has been established. The next step in the modelling process is the conceptualisation. First, the modelling objective and key performance indicators are described. After the objectives of this model are clear, the structuring is further elaborated. Lastly, modelling assumptions are made.

5.1 THE MODELLING OBJECTIVE AND KEY PERFORMANCE INDICATORS

The model used in this thesis is constructed to get a better insight into the transition of the natural gas infrastructure to a hydrogen infrastructure. The different strategies that drive and influence this transition are evaluated. To explore the effect of the different strategies, the model must show the transition over time and not only the end state. The drivers of the transition need to be transparent and subject to different strategies implemented. To get an understanding of the effect of the different strategies, various key performance indicators are monitored over time.

To assure that the results are not linked to the specific set-up of the network, the several randomly formed networks have been created, making it possible to run the different strategies over the different networks.

The key performance indicators should give insight into the performance of the adaption strategies over time. The result of the strategies is evaluated based on three main KPI's.

The first KPI is *the costs* spent to make the transition of the network possible. The energy transition brings along many challenges and investments. The main challenges how to transition whilst keeping a satisfying the demand needed of both natural gas and hydrogen. Investments are needed to upgrade the current natural network to transport hydrogen safely, and the applications that used to run on natural gas now needs to be transformed or replaced by applications that run on hydrogen. The feasibility of the new infrastructure is directly connected with the question if it can be financed. For this reason, the total costs are an important KPI to test different strategies. In this thesis only the network investment costs that are directly related to the network are taken into consideration. This includes the costs of the construction of new pipes, the one-time adjustment cost of a natural gas pipe to allow hydrogen transportation and the costs for the use of tanks that are utilised to deliver natural gas or hydrogen to consumers who are (tempor-

ary) not connected to the correct source.

The *volume hydrogen in the system* is the second KPI. This KPI measures in time the number of nodes that are connected to a hydrogen source or measures the volume of hydrogen that flows through the network by calculating the amount of hydrogen that is delivered to the consumer nodes. Both these approaches might be seemingly the same, the difference however lies in the fact that the different nodes have a different demand and some adaptations have a more significant effect than others. Both approaches indicate how the application of hydrogen evolves. The model monitors the two different KPI approaches in the interface. In this thesis the focus lies on the volume of hydrogen delivered to the end consumers as a percentage of the full potential. The nuance between the two approaches is not the focus of this thesis. This KPI intends to interpret whether there is a different pattern and outcome with the different strategies in this development.

The third KPI concerns *the extent to which the network changes*. Pipes in the network can be left unchanged or can be changed to transport hydrogen. New pipes can be added to the network, and temporary connections in the form of tanks can be included in the network. This KPI focuses on the percentage kilometre of pipes that is left unchanged in regard to the starting state of the network. This is the best indicator to see the results of the strategy on the network itself. At the same time, the percentage of kilometres of pipes that are both newly added and changed are also monitored.

Another additional KPI is *the volume hydrogen* that is exported. The Netherlands wants to maintain the position of transit country for natural gas and wants to extend this position by transporting hydrogen as well.

CO₂ emissions are not included in this thesis. A reason for this is that a significant part of the generated hydrogen is not produced through a green or blue method. Additionally, there is a bigger potential hydrogen demand than the foreseen production. The assumption that is made here is that all the demand will be met. This results in even more unclarity to the origin of the hydrogen in the model. Whether green hydrogen is really CO₂ neutral or carbon-free is debatable. The electricity that is needed for the electrolyse is not always generated in a carbon free way, or the electricity could also have been used for other purposes where because of the lack of electricity a carbon-intensive alternative is required. A full life cycle analysis is needed on the hydrogen production and consumption to clear out at least some of the uncertainties this could be a subject for a thesis on itself. Therefore, in this thesis CO₂ emissions are not considered as a KPI.

5.2 STRUCTURING

5.2.1 Agents

The main actors that play a role in the realisation of the hydrogen network, (partially) based on the natural gas network, are:

- the suppliers of hydrogen and natural gas,
- the consumers of hydrogen and/or natural gas,
- the network operator that is responsible for the physical infrastructure.

This last agent is not included in the agent-based model.

Section 4.1.2 described these different actors. From here on, these actors are referred to as agents in the agent-based model where each agent corresponds to a person, organisation, firm, department or another group (van Dam et al., 2013). The agents are elaborated on below.

Natural gas sources: natural gas sources include both the natural gas that is produced domestically as the natural gas that is imported. The natural gas producers do not have any direct interactions with others. Customers consume the natural gas coming from the natural gas source nodes. The indirect connection between producers and consumers is organised in the form of pipelines or tank transports. The consumption is monitored and will develop over time as more and more consumers of natural gas will make a switch to hydrogen.

Hydrogen sources: hydrogen source nodes have similar properties as the natural gas source nodes, except for the type of gas they produce. In this thesis no distinction is made between the generation methods of hydrogen. Furthermore, the *potential generated quantity* is fixed over time. As shown in table 4.1, the potential demand for hydrogen is higher than the production. In this model, the assumption is made that the demand for hydrogen is leading, and the production will not be a limiting factor. The interaction of between hydrogen producer and customer is similar to natural gas producer and customer.

Industrial clusters: industrial sinks represent the industrial customers that could have both a hydrogen and/or a natural gas demand. Currently, natural gas is most often used for high-temperature processes. The installations of the industrial sink agents use to run on *an initial gas* being natural gas and have a *energy demand*. Furthermore, they have a *utility* to adapt their installations. This is a combination of the investments needed to adapt and the difference in costs and the amount of CO₂ that can be reduced and the extent to which the hydrogen network has processed.

As described in section 4.3, a guarantee could provide security and reduce the investment risk which the agents need to make. For this reason, the industrial sink agents interact with the network operator agent to determine which part of the network will be adapted at what time. This interaction is

also reflected in the utility score.

Electricity plants: electricity generator agents represent natural gas-fired electricity plants. As described in section 4.1.2, the current natural gas-fired plants can be adapted in a way that they burn hydrogen instead of natural gas.

Similar to the industrial sink agents, the electricity generator agents have an *initial gas* on which their installations are adjusted and a *demand* for both natural gas and hydrogen. Also, they have a *utility* to adapt their installations. The electricity generator agents also interact with the network to determine this utility.

Distribution network: the distribution network agent represents both the built environment and the mobility sector that are both connected to the distribution grid. The built environment and the mobility sector are represented in a predetermined *proportion*. Currently, a considerable part of the built environment has a natural gas connection, but alternatives are sought for natural gas. In some cases, hydrogen is this alternative. In the mobility sector, little natural gas is used, but hydrogen is a promising sustainable alternative. This agent has an *initial gas* that it consumes and a corresponding *demand* for both natural gas and hydrogen. Their *utility* to adapt to hydrogen is higher than the other sink nodes. However, the distribution network characterises itself as very extensive to reach out and connect entities over a large area. In terms of length, a big part of the infrastructure needs to be adapted for hydrogen.

Natural gas export: natural gas export agents represent the points where natural gas exits the network to neighbouring countries. These are predetermined quantities that are fixed. These agents thus have an *initial gas* they export, which is natural gas and does not change, and a corresponding *demand* which is the trading volume. The difference with this agent though is that this agent will not adapt to hydrogen and will retain their demand for natural gas. This they communicate with the network.

Hydrogen export: hydrogen export agents represent the points where hydrogen exits the network to neighbouring countries. There too are predetermined quantities that are fixed. Similar to the natural gas export, these agents have an *initial gas* they export, which is natural gas, and a corresponding *demand* which is the trading volume. The hydrogen export is a new ambition that the Netherlands want to fulfil. As described in the strategy section, one of the common objectives is to establish the possibility to import and export hydrogen through the network. In this case, this is communicated with the network.

Network connection node: the network connection agent is a node that structures the infrastructure. The different source and sink agents are connected through these connection nodes. They do not have any other characteristics other than that they can receive both hydrogen and natural gas, or

one of both. This depends on the state of the network and how far it has transitioned.

5.2.2 Objects

The infrastructure is the object that connects the source nodes to the sink nodes through the connection nodes. An object can transmit both hydrogen and natural gas; however, this cannot occur at the same time. A specific infrastructure connection transmits one of the two. The way of transmission can occur via a pipeline- or a tank. Summarised, a connection can have the following different forms; a natural gas pipeline, a hydrogen pipeline, a natural gas tank transport and a hydrogen tank transport. The two different objects, pipelines and tank transport trajectories, are described below.

Pipes: a pipeline transmits one gas type at the beginning of a time step. The choice can then be made whether to leave this intact or adjust the pipe so that it can transmit a different gas. Whether or not a pipe can be changed, is determined by the neighbouring nodes on both sides of the pipeline and the gas type they have access to. This interaction between the nodes and pipes happens continuously and is always updated. The interaction between the nodes and pipes is displayed in figure 5.1. When a pipe is changed, the corresponding costs are deducted from the budget. A new pipeline can also be added. This can happen between any two nodes where no pipeline is currently available. This interaction is shown in figure 5.2.

Tanks: This can be by rail (train) or by road (truck). The choice can be made to allocate a tank for a specific connection. A tank is placed on a trajectory when a node does not receive the gas type it desires. The combination of the utility score and the gas connection a node has, determines if the node is connected correctly. This determination needs to be made every time step. When a tank transport is allocated, the corresponding costs need to be deducted from the budget.

A strategic choice can be made to construct a new pipeline on a location where tank transport is often used. In this case, the corresponding costs of the new pipeline are also deducted from the budget.

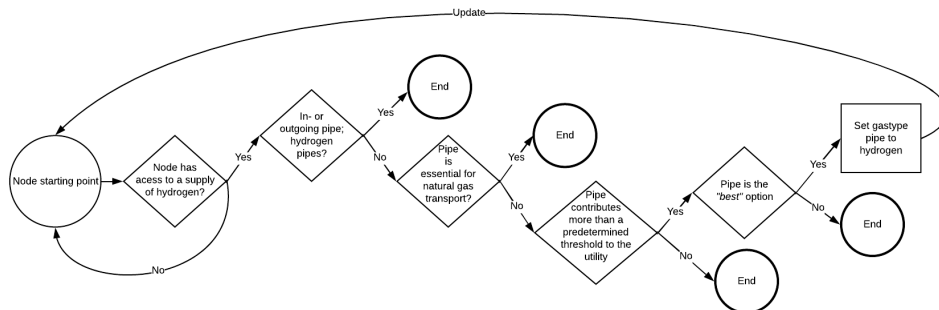


Figure 5.1: Decision process for the adaption of edges

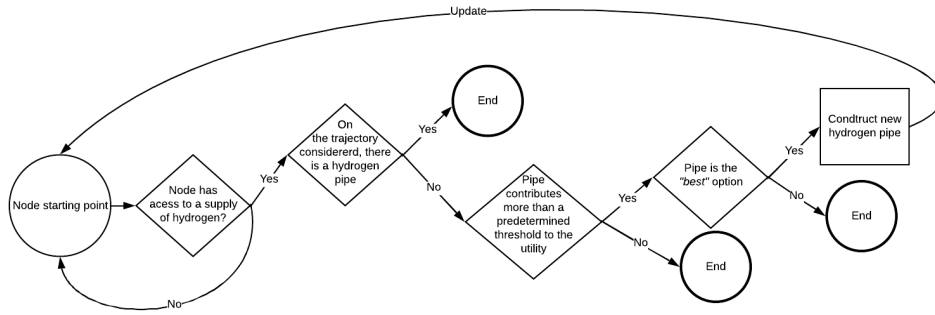


Figure 5.2: Decision process for the construction of new edges

5.2.3 Network adaption

As there are costs and infrastructure consequences of the transition of the network, the transition needs to be carefully considered. The utility of a pipeline trajectory determines the need and the value for the investment. A choice has to be made which pipe first as not everything can be done simultaneously. The overarching strategy is to have a minimal investment with high results, this is served best by either transition the low-cost trajectories, or the trajectories with the highest utility, or a combination of both. The importance of the trajectory can be based on the maximal utility of one of its connections, on the average utility of all of its connections or a ratio of the utility of the trajectory divided by the costs needed for the transition. How the utility score is calculated, is described below.

The utility score is a combination of the adaption needed by the end-user and a factor that finds its basis in the transition dilemma, as described in section 4.3.

The double-sided dependency and trust between the TSO ensuring the infrastructure, and the consumers ensuring that the network is employed, is partially translated into a utility score that reflects on and responds to the trust that is needed for the infrastructure to be developed and be changed. When the utility score is within certain predetermined boundaries, there is an assurance that the consumer will use hydrogen. When the utility score is under a predetermined threshold, no hydrogen will be consumed. The different actors react to the level of which the infrastructure is already developed. The more it has matured towards themselves, the higher their utility score gets, as the assurance that they will be connected, gets higher.

All nodes have a utility score between 1 and z , and this score is adjusted when a transition of a trajectory takes place. This utility score is a build-up of the starting value (SV) which is specific for the type of sink node that is configured with a random variation. Consequently, a transformation of the distance between the concerning node and the closest connection node that is connected with hydrogen is calculated. This is a number between 0 and 1. This is added to the starting value. To assure that the utility score is an equal balance between the starting value and the distance to hydrogen, the

distance score is multiplied with the average starting value.

The utility score of a specific sink node is:

$$Utility = (SV_{sink} - a) + (b \times (1 - \frac{1}{c}) \times D_{sink})$$

Where:

SV-sink: Starting value of a sink type

a: Random deviation of the starting value

b: Average value of the SV

c: Maximum distance between two nodes in the network

D_{sink}: Distance between the node in question and the closest by hydrogen connection node

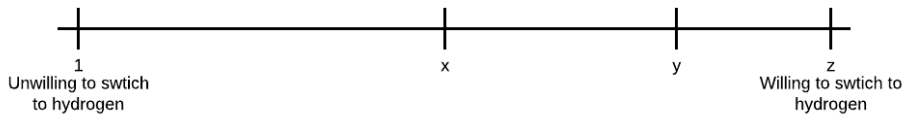


Figure 5.3: Range of values of the utility score have

As can be seen in figure 5.3, the utility score can thus take on a value between 1 and z. If the value is at x, which can be defined in the model, the sink node is ready to be adjusted to hydrogen and with this is able to receive hydrogen. At a score above y, the adjustments should have already been made, and therefore this node should be connected to a hydrogen source. Nodes with a score below x should always be connected to a natural gas node. The natural gas export sink node forms an exception on the whole described above, this node gets the utility score of 1, which does not change.

The utility score of the nodes is translated to the pipes where, based on a tactical decision, the pipe either takes on the average utility of its connecting nodes, or the maximum utility of one of its neighbouring nodes.

Local optimisation as system driver

The driver behind the system behaviour is local optimisation. It is important to note that the model applied is a simulation model and not an optimisation model. Based on the local state of the system, the decision needs to be made to apply a certain change to the network. This approach for evolution is supported in the literature.

"Evolution, given its algorithmic nature, does not produce the 'best possible' solution. In other words, evolution is a local, not a global optimiser, creating solutions that are good enough for the given situation" (Nikolic et al., 2008)

In case of infrastructure evolution, the optimisation that occurs can be based on different criteria. In the literature, most of these are focused on costs or environmental impact (Kim and Moon, 2008; Hugo et al., 2005; Stephens-Romero and Samuelsen, 2009). The environmental impact is challenging to grasp in the research done for this thesis, as it is difficult to get information on this matter. Nevertheless, in this research, the infrastructure is already established and will change. This change, compared to creating a completely new infrastructure, has a lower impact on the environment. For this reason, in this thesis the costs are implemented as one of the driving forces on which this local optimisation depends. Adding utility as another optimisation criterium does not affect the fundamental principle of optimising locally, and the effect of the inclusion of utility as a local optimisation criterium is one of the focus points in this thesis.

As described above, this model is not an optimisation model, but every step the best choice is determined based on the local state of the system. With this, the transition of the system becomes path-dependent, as the decision of the previous step influences the next step, and the next step. Optimising the whole system with the help of an optimisation model does not take into account path dependency. The fact is that numerous stakeholders, all with their own specific needs, are involved in the transition, and that it is not likely that overall optimisation can satisfy all stakeholders needs. Often decisions are made based on local information.

Consequently, in this model, *local* optimisation is applied to determine which change to make to this network. Different criteria for this local optimisation are subject to experiments in order to determine the effect of the criteria on the system behaviour.

5.2.4 Environment

The model environment describes the exogenous system components which influence the system but cannot be influenced by the sub-components of the system itself (van Dam et al., 2013). In this model, the exogenous variables are:

- The starting topology of the network,
- The costs of the different infrastructure options,
- The amount of budget that is available per time step,
- The total run time of the model.

The different adaption options have different costs and this in combination with the budget, determines the decision space in every time step. Each time step in the model is expressed as a tick. One tick corresponds to one year, and the choice is made to simulate the model until 2050, making the run time of the model 30 years. In the section below, more insight is given into the topology of the network and how this can be seen as an exogenous component.

The topology of the system describes the beginning state of the network, which is the fundament from which changes are made.

The topology of the network

The network configuration consists of a number of nodes, the location of these nodes and the edges between the nodes. The network is generated by placing one connection node after another on a random place. Whenever a node is added, it creates a link with the node that is in the nearest proximity. After all connection nodes are set up, the source and sink nodes are added. Similar to the connection nodes, these are placed on a random location, and the source and sink nodes then create a link to the connection node that is closest by.

To uncover the effect of a topology of a network on the effectiveness of a strategy, different starting positions for the networks are used. These starting positions of the networks differ in the sense of the location where the nodes are located. With a different location, different connecting links are formed, and the network will be different. Nevertheless, the way the networks are configured is similar. Additionally, the number of nodes that are created is the same in all replications. An example of two different topologies is given in figure 5.4. In this image, it is visual how only the location of the nodes influences the starting position in the network. For further analysis, a starting network based on the Dutch low calorific natural gas network is configured.

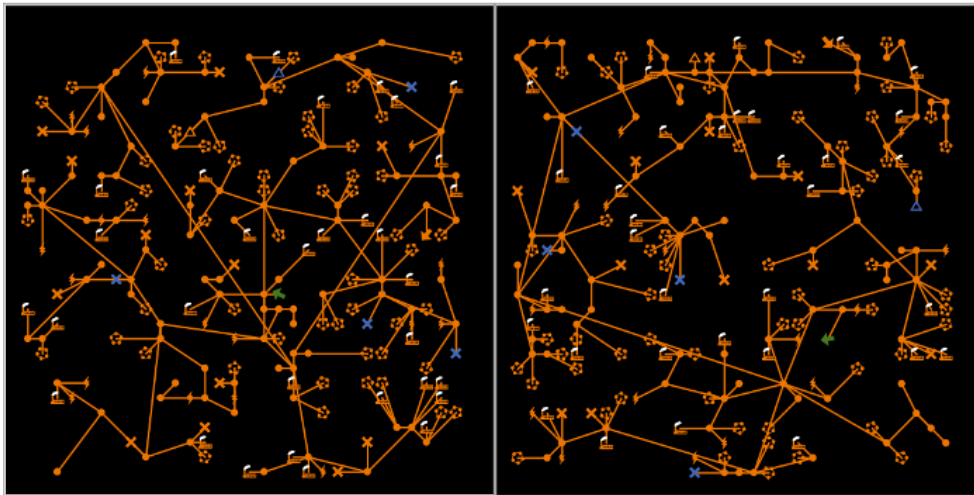


Figure 5.4: Two examples of different starting topologies based on different location of nodes

5.3 MODEL ASSUMPTIONS

The following assumptions, and the reason behind them, are listed below:

- The input variables stay constant over time. The demand of the sink nodes remains fixed; the supply of the source nodes stays constant.

Additionally, the costs of the different options maintain the same and the assumption is made that no ground-breaking innovation will occur, lowering the costs of the adaption of the network. The reason for this assumption is to ensure that the model does not get too complex.

- There will always be enough natural gas and hydrogen to meet the demand. The reason for this assumption is that the model would become too complicated if the agents would compete with each other for the available gasses. This model aims to show the development of the network and not game theory in a scarce market.
- There will always be a constant natural gas export. The Netherlands has an international role within the gas export and is seen as having a 'gas roundabout'. As the running time of the model is until 2050 and not after, the assumption is made that this role will be left unchanged.
- The natural gas consumption will directly be replaced by the hydrogen consumption in the volumes that are indicated in table 4.1. First of all, these numbers seem reasonable when taking into account that three times the amount of hydrogen is needed to deliver the same amount of energy and that some sectors will have a broader range of alternatives than others while becoming carbon-free. Secondly, without this assumption, the nodes would need a connection with both a hydrogen as a natural gas source. In this case, no network adaption would occur, but the natural gas network would need to be duplicated for a new hydrogen network.
- In line with the previous assumption, the distinctive situation in the Netherlands, where a significant part of the main transmission network is laid out double for different qualities of gas, is not taken into account. As described in 4.5.1, the choice for this assumption is based on the fact that this research aims to get a better understanding of the transition of a network. With a double network, no real transition will occur. The second reason for this assumption is that the double network is unique for the Netherlands, and therefore the results will be more generalizable when not considering the double network.
- In order to make this previous assumption, no distinction will be made between the high and the low caloric gas in terms of distinct end-users who only use one of both.
- The last assumption is that the capacity of the infrastructure is always sufficient for the demand. This is indicated in the report by Gasunie and TenneT (2019).

5.4 SUMMERY CHAPTER 5

This chapter answers the second sub-question by presenting a conceptual model. The model's objective is repeated, and key performance indicators are defined to evaluate the model's objective. The conceptualisation then

continues by describing the agents, the objects and the environment. The actors in the model represent the different source and sink nodes. An additional connection node is included to shape the network. Two different objects are defined; pipeline and tank trajectories. These objects connect the different agents in the model. The environment consists of a starting topology, prices for different transition options, a total budget and how time is represented in the model.

Additionally, further elaboration on the model behaviour is given. This behaviour is driven by local optimisation of cost, utility or a combination of both. In the next chapter, the implementation of the conceptual model into Netlogo to an agent-based model is described.

6

MODEL FORMALIZATION

This chapter describes how the conceptual model is translated into the agent-based model. First, the concepts are formalised by introducing the model narrative and visually showing how the different nodes and edges interact with each other. The next step is implementing the model narrative into Netlogo by translating it into code. Lastly, the model inputs and outputs are discussed.

6.1 CONCEPT FORMALIZATION

The goal of this research is to uncover the effect of strategies on the transition of a new infrastructure that is based on an already established infrastructure. To accomplish this goal, a network with a specific starting composition will be subject to the different tactical options which together can form strategies. These tactical options are described in 4.5.3 and the tactics with their corresponding options are shown in table 6.1.

Tactics	Options
Priority of changing network	"Lowest cost option", "Option with the biggest average utility", "Option with the biggest maximum utility", "Option with the highest utility/costs" " The strategy changes from cost to utility/costs to utility"
Time between the swichting of priority change options	Between 0 and 30
Prioritize the export of hydrogen and natural gas	"On" or "Off"
Construct pipes between every possible nodes	"On" or "Off"
Construct pipes on an intesive used truck connection	"On" or "Off"
After how long should these trucks be constructed	Between 0 and 30
How is the budget allocated over the years	"equally", "Increasing" or "Decreasing"
How is the budget allocated between the infrastructure, the industrial sector, electricity sector, and distribution grid	Between 0% and 100% with a sum of 100%

Table 6.1: Formalization of the tactical options

6.1.1 Model narrative

The model narrative describes the procedures in the model that are a result of the interaction of the actors with the objects and environment.

The principle in this model is that there is an existing network of nodes and edges that can change gas type and/or new edges can be added. The model starts with receiving a budget to make these changes to the network. Every year, the network can make changes as long as it has a budget, and as long as there are options to change that are worth changing.

The first requirement for a pipeline to be an option to change to hydrogen

is that that pipeline is in connection to a node where hydrogen is already available. These are nodes that are either a hydrogen source or an import point, or other nodes that are already connected to hydrogen and thus are in connection to these sources or import points. There are two conditions under which some pipes cannot be changed. This is the case when a pipe is essential for the transport of natural gas. Essential natural gas pipes are pipes that are needed for the export route of natural gas, when this is chosen as a tactic, or when a pipe connects the natural gas sources to the grid.

Whenever there are more plausible pipes that satisfy the conditions described above, a choice needs to be made which pipe needs to be changed first. Here the second tactic comes in. This choice can fall on the cheapest option, the highest utility, the highest utility divided by costs or a mixture of the three. An addition tactic is allowing new pipes to be constructed between every two network points. The first condition, that a pipe change option is only possible when there is a connection to a hydrogen point, also holds for these potential new pipelines.

After this first transition, it is possible that a changed pipe prevents the transportation of natural gas to a demand point, and this demand point is not ready to receive hydrogen. In this case, this point still needs to be supplied with natural gas by a tank. It is also possible that a specific connection point already needs hydrogen, as it already made the investments for the transition, but the choice has not fallen on connecting this point to the hydrogen network. In this case, hydrogen needs to be delivered to this point by a tank.

The third tactic is included now. The choice can be made to construct new pipelines in a situation where tank transportation is allocated more than a specified time.

The change that has been made is now updated. The new pipe has supplied hydrogen to one or more points, and with this, it creates new possible options to pass along the hydrogen.

In the meanwhile, the utility score of the nodes is updated. As described earlier, this utility score is the combination of characteristics of the demand node in question, and the distance to the closest by hydrogen point. This first is a combination of a starting value, that is specific for the sector, which increases in time. The second, the distance to hydrogen, is updated continuously to stay accurate.

The utility of the nodes is transferred to the pipes, and the pipes gets the average utility score of the connecting nodes, or the maximum value of both ends.

The whole process of updating the gas type of nodes, calculating the distance to hydrogen and updating the utility score is used to determine all possible options to change the network. Based on local optimisation, the option to change is selected, after which the transition is made. Whenever needed, tanks are allocated. This sequence continues until there are no suit-

able changes to make, or when the yearly budget is below 0.

There is an additional tactic that can be applied to the way the budget is allocated over the years. First of all, the total budget can be divided equally over the run time of the model, a small portion of the budget can be spent in the early years, and the yearly budget can increase over time, or the biggest portion of the total budget can be allocated in the beginning years. This affects the number of transitions that are made in either the beginning or at the end, which also influences the option space over time.

6.1.2 Model interactions

The interaction between the different nodes and edges, as described in the conceptual model and in the model narrative, are represented and visualized in figure A.1. A larger version can be found in appendix A.

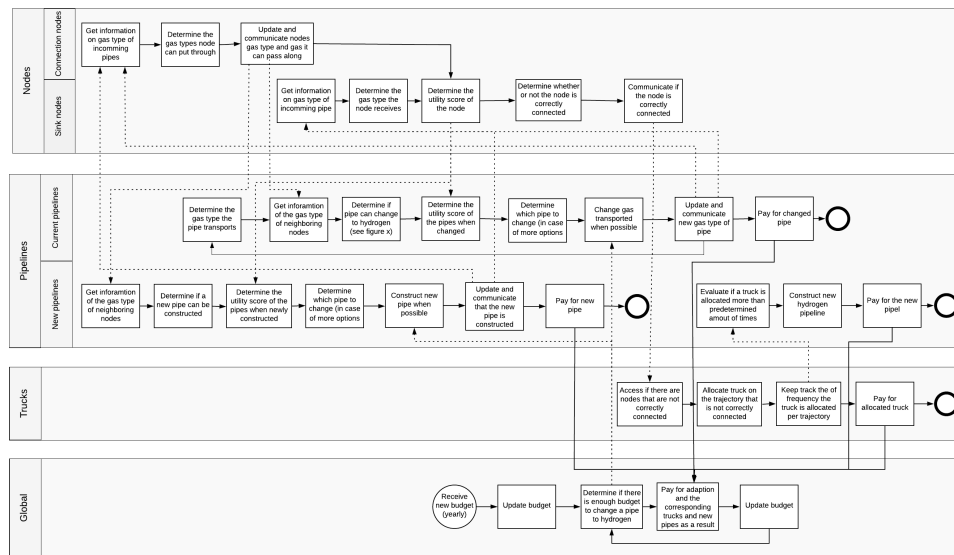


Figure 6.1: BPMN inspired diagram

6.2 MODEL IMPLEMENTATION

In this step, the conceptual model described in the previous chapter, and the model narrative is implemented in the model environment Netlogo 6.1.1. Throughout the code, comments are made to describe what a section of code is doing. This allows a better understanding of the code while constructing the model. It also helps to keep track of the steps. The images in figure 6.2 show how the network changes from a natural gas network (orange) to a hydrogen network (blue). One of the main advantages of Netlogo is that it has a strong visual representation of the code, and this makes it easy to see what is being coded.

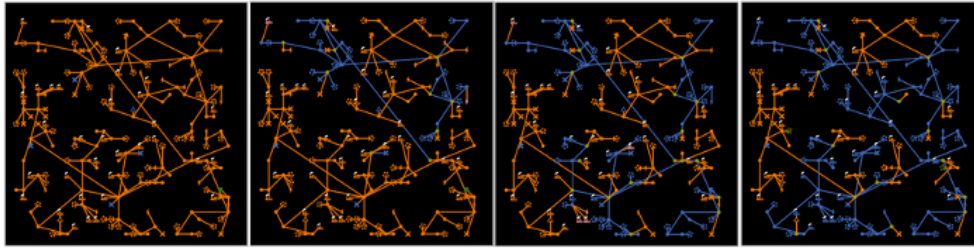


Figure 6.2: Model world changing during the run

The interface of the model is shown figure 6.3. There are input windows, sliders, switches for the input and graphs and monitors for the output. In the next subsection, these are discussed more elaborately.

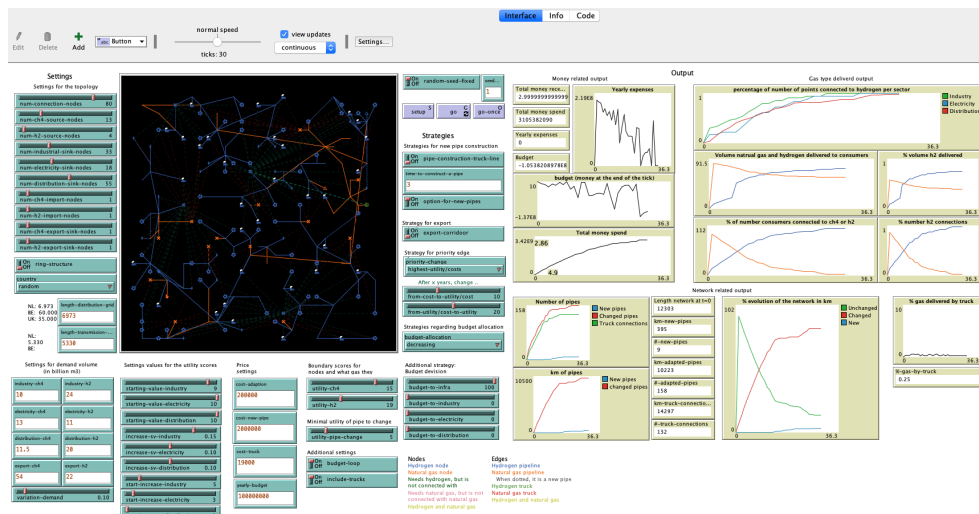


Figure 6.3: Model interface

6.2.1 Model input and parameterization

Figure 6.3 shows a variety of sliders, switches and input monitors where the settings of the model can be managed. It is a deliberate choice to include these parameters in the interface where they can be adjusted by users instead of incorporating them in the code. The reason for this is to allow additional scenarios to be run. This model does not intend to estimate and predict the transition of the Dutch gas grid, but it uses this representation of a natural gas grid as a way to study and understand influences on the process of the transition. While including the settings in the interface, it eases the process of studying this change, and it makes it possible to adapt the situation to other settings and study those as well. Additionally, this thesis is curiosity-driven, and the wide variety of input parameters enables different setting additional outcomes from this model.

There is a difference between the input parameters and the tactics with which strategies can be constructed. The whole model can be configured in different ways. When the settings are varied in the different scenarios,

the differences in outcomes becomes huge. When testing every setting, the outcomes vary much, making the outcomes more or less meaningless. The model in this thesis makes it possible to test a variety of things, the choice has fallen to test the effect of strategies. For this, the rest of the settings is left unchanged. However, for further use or experimentation, it is also possible to test a fixed approach created by the tactical options and test this approach on different model settings.

In figure 6.3, the parameters can be divided into six categories. The parameters are located on the left and underneath the visual representation of the network.

- The first category of settings controls the topology. Here the number of nodes per different type of node can be configured. Also, the choice can be made to use a random topology, in the form of a ring or a spread out network, or the topology of the Netherlands, Belgium or the United Kingdom.
- The second category determines the gas demand in billion m³ per sector. It is possible to divide this demand equally among the nodes, or include a variation between the nodes.
- In the third category, it is possible to adjust the settings for the utility score of the nodes. This utility score is a combination of characteristics per sector concerning the investments they need to make, and a reassurance of some kind that the infrastructure has evolve toward the node. The settings for this first part can be determined in the setup by setting the value where the starting value starts, how much it increases as time evolves and when the value starts. This can be adjusted per sector separately.
- The fourth category enables the user to indicate the price options of the different ways to adapt the network; change a pipe, construct a pipe or to deliver gas by a tank.
- The fifth category, the boundary values of the utility score as described as "x" and "y" in section 5.2.3 can be determined. It is also possible to determine a minimal utility value a pipe needs to have before making a change.
- The last category includes settings that make the model simpler. Here the choice can be made only to have one change of the network per time step, independent of the budget that is available. It is also possible to leave out the tanks that could supply gas.

A more elaborate explanation of the chosen parametrisation can be found in appendix B. The choice for the values is either bases on information found in literature or reports, or assumptions are made. This is also described in B.

The settings for the different strategies, as shown in table 6.1 can be chosen on the right side of the interface.

6.2.2 Model output and visualisation

The output that the model shows, coheres with the chosen KPI's that can be found in 5.1. The output is visualised with the help of plots and monitors.

- The first category of output is related to money and budget. It shows all the money received, spent and the intermediate expenses.
- The second category is related to the transition. The development of both the volume and number of consumers is monitored as well as the different sectors independently.
- The third category of output reports the development of the network. For this, it looks at the number and kilometres of pipes that are left unchanged, changed to hydrogen or are newly constructed over time. The amount of gas transported by temporary gas connections is also monitored.

6.3 MODEL VERIFICATION

Verification checks whether the conceptual model is correctly translated to model code (van Dam et al., 2013). This process of verification occurred parallel to the model formalisation, as well as after the model was finalised. The model was constructed iteratively, and at every step it was checked if the intent of the code was formulated in accordance with the design. The modelling environment of Netlogo lends itself for verification during the modelling process as it is a visual environment. An example of verification during the process of model formalisation is the use of output monitors where intermediate outputs were followed and copied to excel. Calculations by the model were replicated in Excel to check if the same output per step was generated.

When the model was finalised, verification methods described by van Dam et al. (2013) were applied. These methods comprise of extensive code walk through, recording and tracking agent behaviour, interaction testing limited to minimal model and multi-agent testing. The execution of these methods is described in appendix D with the conclusion that the model is implemented correctly.

6.4 SUMMERY CHAPTER 6

The implementation of the conceptual model into the Netlogo software is described in this chapter. First, the strategies that are a focal point of this thesis are formalised, and the model's narrative is formulated. Then the translation to code is completed, and the input variables of the model are discussed. A distinction is made between the input variables that are input parameters and the different settings for the strategies. Additionally, the model is verified. The next chapter describes the experiments that are performed with the model.

7 | EXPERIMENTATION

In this chapter, The impact of different starting points of the network is discussed, followed by the setup of the experimentation.

7.1 VARIABILITY TESTING IN A BASE CASE SETTING

In this thesis, four different tactical options are explored. For some tactical options, different choices can be made, leading to 6 different tactics. For each tactic, different setting can be applied. The variety of all settings makes it difficult to discover the effect of a tactical option, as a tactical option can be executed in combination with other strategic choices. Table 7.1 indicates the different tactics and the variety of settings per tactic. When all possible settings are combined, a total of 1.566.000 different combinations are formed. Not all combinations of strategy options are evaluated. First of all, it would take extremely long to run all these experiments, and second, the range of results would be broad, and interpretation would become impossible. Therefore, a base case scenario is constructed by choosing a setting for every tactic. This way, specific experiments can be run on this base case to monitor the effectiveness of individual tactics. The last column in table 7.1 indicates the setting per tactic for the base case.

Tactics	Options	Settings	Choice for base case
Priority of changing network	5	Lowest cost option The biggest average utility The biggest maximum utility The highest utility/costs change from cost to utility/costs to utility	The highest utility/costs
Time between the swichting of priority change options	435	2 numbers between 0-30, 2nd > 1st	10 and 20
Prioritize the export of hydrogen and natural gas	2	True False	Ture
Construct pipes between every possible nodes	2	True False	True
Construct pipes on an intensively used tank connection	2	True False	True
After how long should these tanks be constructed	30	Number between 0 - 30	3
How is the budget allocated over the years	3	Equal Increasing Decrasing	Equal

Table 7.1: Strategies options and their settings

One hundred replications with different starting point of the network have been run on the base case to analyse the effect of the difference in the starting network on the results. As described in section 5.2.4 in every replication, the starting topology is different. The base case scenario comprises of a combination of tactical setting. The setting per tactic is indicated in the last column of table 7.1. These settings are chosen as these seem to be likely. The choice of the combination of settings in this base case is not leading for further results. This base case is used to examine the effect of the starting

point of the transition in specific network on the results. The effect of the tactical options is tested individually in the experiments, and the results will be based on the results of these experiments.

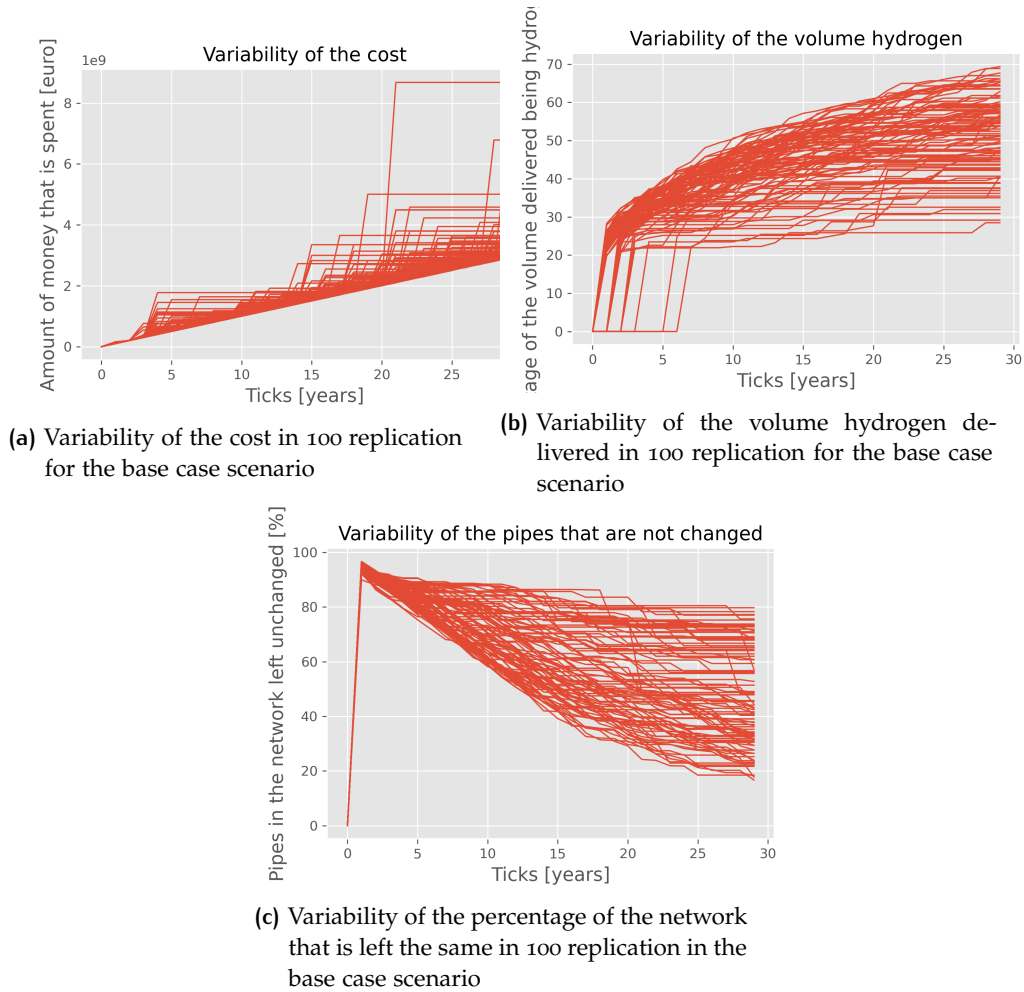


Figure 7.1: Variability testing of the KPI's in the base case scenario over full model run

Plot 8.22a, plot 7.2d and plot 7.1c show a wide range of the results for the 100 different runs. Especially when looking at the volume of hydrogen that is delivered, and the amount of pipes that are left unchanged, the range is considerable. This is also confirmed by the box plots in appendix F that show the the values of the KPI at the end of the model run. The range of the cost is less diversified than the other two KPI's.

Considering the relation between the different KPI's, the following can be said; the relation between the costs and the amount of hydrogen delivered is non existing in the base case with a correlation coefficient of -0,18. The relation between the volume hydrogen delivered, and pipes in the network that are left unchanged is strong. This is a negative linear connection with a correlation coefficient of -0,93. The amount of hydrogen that is delivered increases as fewer pipes stay unchanged. This also makes sense, new pipes need to be added, or natural gas pipes need to be changed in order for consumers to receive hydrogen. The plots that show these relationships can

be viewed in appendix F.

The way the network initially is set up strongly determines the evolutionary path it takes. In order to mitigate the effect of the different topologies, the same starting topologies will be applied in all scenarios.

7.2 EXPERIMENTAL DESIGN

The initial experimental design comprises of a total of 35 scenarios that will be analysed in six experiments. The four main KPI's that will be reflected upon in these experiments are the total costs, the volume hydrogen delivered as a percentage of the potential, the amount of hydrogen that is exported and the percentage of the network that has stayed the same. Table 7.2 shows the setup of the experiments. A scenario represents a combination of tactical setting. Table 7.2 shows the tactical settings that are applied per experiment and the number of scenarios this then creates. A full overview of all the settings per strategy is given in appendix G. When running the experiments, the same set of seeds will be used in the experiments. This way, all tactical options will be tested on the same starting networks. This assures that the results are not accidentally showing behaviour that is related to the topology but can be regarded as behaviour caused by the strategy or tactic. Furthermore, all strategic settings that are not named in the experiment design will be set to the standard settings as described in the base case scenario.

Experiment	Tactics tested	Settings		Number of scenarios	Replications
1A	Priority pipe change Option for new pipes	Cost Mean utility Max utility Utility/cost Mixed	True false	10	50
1B	Time between first and second strategy Time between second and third setting	10 ; 20 1 ; 16 15 ; 29 15 ; 16		4	50
2	Export corridor	True False		2	50
3A	Option new pipes Construct pipes on tank connections	True False	True False	4	50
3B	Construct pipes on tank connections after x years	1, 3, ..., 27, 29		15	50
4	Budget allocation	Equal Increasing Decreasing			

Table 7.2: Overview of the experiments

7.3 EXPERIMENTING WITH THE EFFECT OF THE STRATEGY OPTIONS

To uncover the effect of the four tactical options on the way the hydrogen network evolves, six experiments are set up. For some tactical options, two experiments are needed to grasp the full impact of the tactic.

7.3.1 The priority of which pipe to change

The first tactic aims to find out which pipe should be changed or newly constructed. At each step in time, this decision is locally optimised based on one criterium. However, there are more criteria that can be chosen. The effect on the outcome caused by the chosen criterium is the focus of the experimentation with this tactic. A more extensive explanation of the local optimisation applied in this research is described in 5.2.3. As described in 4.5.3, this local optimisation can be based on:

- The lowest cost,
- The highest mean utility - that is the average utility of the nodes the pipeline is connected to,
- The highest maximal utility - that is the maximum utility of one of the nodes it is connected to,
- The highest utility/costs – that is the average utility of the nodes the pipeline is connected to, divided by the costs of that pipeline,
- Or a strategy where for
 - Year 0 - 10, the lowest cost criterium is used,
 - Year 10 - 20, the utility is divided by cost is used,
 - Year 20 – 30 the pipes with the highest utility are constructed or changed.

Experiment 1A

The first tactical option is broken down into two different experiments, the first aims to test the five options of the priority which pipe to adapt, with or without allowing new pipes to be constructed between every other point in the network. The hypothesis here is that the largest difference in the outcome will be seen allowing new pipes to be constructed under the setting of giving priority to the pipes with either the highest average utility or highest maximum utility.

Experiment 1B

The second part of this experiment focuses on the strategy option where a changing in the settings is applied. To limit the number of experiments, only the duration of using a specific setting will be varied. The sequence of the settings is not changed.

- In the first experiment, all three settings will run for ten years; starting with cost, then utility/cost and finishing with utility. The utility option is based on the average utility.
- In the second experiment, the setting using cost is not included.
- The third experiment leaves out the utility/cost option.
- The fourth experiment starts with the strategy of lowest costs and then moves to local optimisation based on the highest utility/cost while leaving out the option of local optimising based on maximum utility.

The logic behind the sequences is that with the option of low costs, a primary starting point of the network is formed without focusing on connecting the consumers to the hydrogen network. Then the switch is made based to utility/costs. In the last ten years of the experiment, the focus is on connecting the last consumers, and not focusing on costs. The hypothesis here is that starting with the considering cost is a good strategy. If there is only a focus on the highest utility, this might lead to expensive investments at the start, blocking the expansion of the transition when the largest part of the budget is spent.

7.3.2 The effect of an export corridor

The second tactical option evaluates the prioritising of the export and import flow of hydrogen and natural gas in the network. The experimentation with this tactic aims to find out how the prioritising of export and import impacts the speed of transition and the final level of transition for the whole network.

Experiment 2

There are two options: One strategy option is to prioritise the export-import by constructing an export corridor. The second one is not to prioritise the export and import of hydrogen and natural gas.

The working hypothesis is that in the long run, establishing the corridor is beneficial as this allows crucial pathways to be laid out with both hydrogen and natural gas. Investments will be made in the beginning, and therefore the system will benefit from these investments in the years to follow. The total volume exported hydrogen will be higher with the export corridor than without.

7.3.3 The effect of newly constructed pipelines

In the third tactical option, the bases for allowing to construct new pipes to the existing network using specific criteria is evaluated. In this model, there are three criteria that can be used to decide on allowing to construct new pipes to the network.

1. A pipe will be constructed on a trajectory where a tank is allocated more than three times - this is the setting in the base case scenario-.

2. A new pipe is added is when this is decided during the local optimisation processes, which is based on the strategic choice that is discussed for the first strategy option. This new pipe can be constructed between every two nodes when it meets the requirements.
3. When a pipe is needed for the export of both hydrogen and natural gas, a new pipe is constructed in order to transmit both gasses.

Experiment 3A

Experiment 3A observes the situation when the first two criteria for constructing a pipe are allowed. Building a pipe based on criteria 3, when needed for the export corridor, is not included in this experiment, as this option is already examined in experiment 2. The hypothesis is that the construction of a pipe when this is based on the local optimisation criteria, is beneficial for the system. The construction of a pipeline based on a tank connection will contribute relatively little, as this option is not preferred by the system itself.

Experiment 3B

This second experiment will look into the default setting of allowing building a pipe after three years using a tank connection and to determine if there is an optimum for the number of years to invest in a new pipeline based on a tank connection. The hypothesis is based on the hypothesis in experiment 3A, where it is said that this construction in the first place is not feasible. Consequently, it is expected that the longer it takes to construct a new pipe on the tank trajectory, the smaller the chance that fixed connections will be constructed, and the more the system will benefit.

7.3.4 The effect of budget allocation over time

This strategy option aims to find the optimal way to spend a fixed budget over time. The potential value increase of the budget caused by an interest rate of the budget which is not spent, is not taken into account.

Experiment 4

The assumption that is made, is that there is a fixed budget available for the network transition for 30 years. The budget can be divided into equal parts, and the same amount can be allocated every year, or it is possible to increase or decrease to money allocated over the years. This strategy aims to find out how the KPI's develop based on how the budget is spent over time. The working hypothesis in this case is that it is preferable to allocate the biggest portion of money in the beginning, as this way, the system can benefit from these important first investments over a longer period of time.

7.4 EXPERIMENTING WITH COMPREHENSIVE STRATEGIES

Based on the outcomes of the different tactical options in regard to the total expenses, the percentage hydrogen that is delivered in the system and the total volume hydrogen that is exported, comprehensive strategies are constructed. Not only are the strategies compared with each other, a reflection is made whether the effectiveness of a strategy is connected to centrality measures of the starting point of the network.

7.5 DETERMINING THE EFFECT OF THE COMPREHENSIVE STRATEGIES ON THE NETWORK IN THE NETHERLANDS, BELGIUM AND THE UNITED KINGDOM

To finalise the experiments, the different strategies are tested on topologies that are based on the topology of the Netherlands, Belgium and the United Kingdom. The in topologies based on a country, the structure of the transmission infrastructure is adopted, which is shown in figure 8.3.2. The placement of the source and sink nodes are, with the exception for the Dutch scenario, random. The structure of the Dutch based gas infrastructure is based on the low calorific gas network and a fixed location to the source nodes is given. A more detailed explanation of the construction of the country topologies is provided in appendix E.

As described in section 7.1, there is an effect of the topology on the results. The difference in the starting arrangement of the networks used in the first experiments are only based on the location of the nodes and with this the pipes that are formed to connect the nodes. The way the networks are set up is similar. This was described in section 5.2.4. In these last experiments, a whole new setup of topologies is applied based on actual the infrastructure of countries. Applying the strategies on the topologies of these three countries enhance the insights of the effect of those strategies on different topologies, and it also provides country-specific insights how the strategies could help to ensure a hydrogen transition.

In regard to the different topologies, the plots in 8.3.2 show that the topologies have a different average closeness centrality and betweenness centrality. A high betweenness centrality indicates that there is a high number of nodes that are essential regarding the shortest path from one node to another. It can be seen that the starting topology of the Netherlands has the highest betweenness centrality. The fact that the Dutch grid is set up in a way where ring-like structures can be found causes this high betweenness centrality. The shortest path from one node to another often goes past the same nodes. The random starting topology has a lower betweenness centrality, which can be traced back to the fact that this topology is scattered out more. The closeness centrality indicates the distance between the nodes. The lower the centrality measure, the further away the node is to other nodes in the network. Figure 8.22b shows that the Netherlands and Belgium have a low

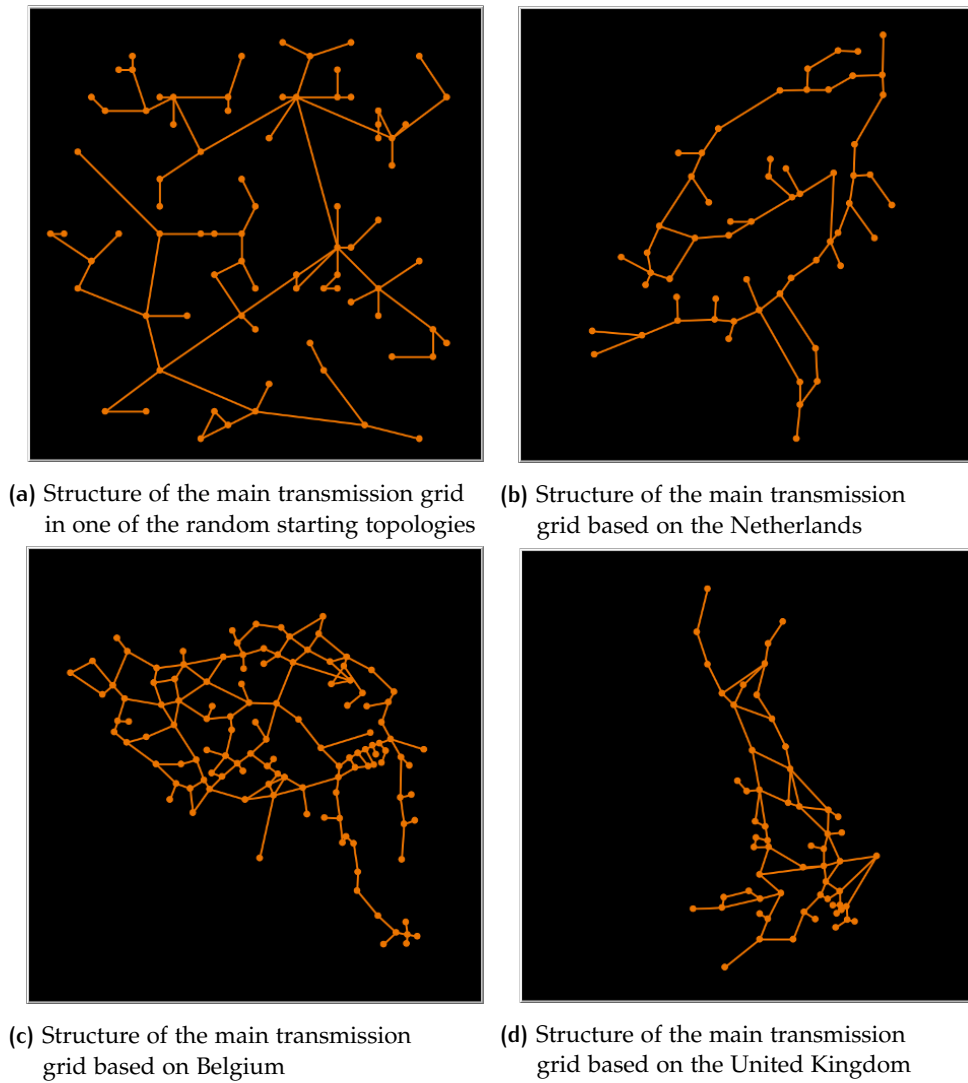


Figure 7.2: Centrality measures for the starting networks in the case of a random topology, a topology based on the Netherlands, Belgium or the United Kingdom

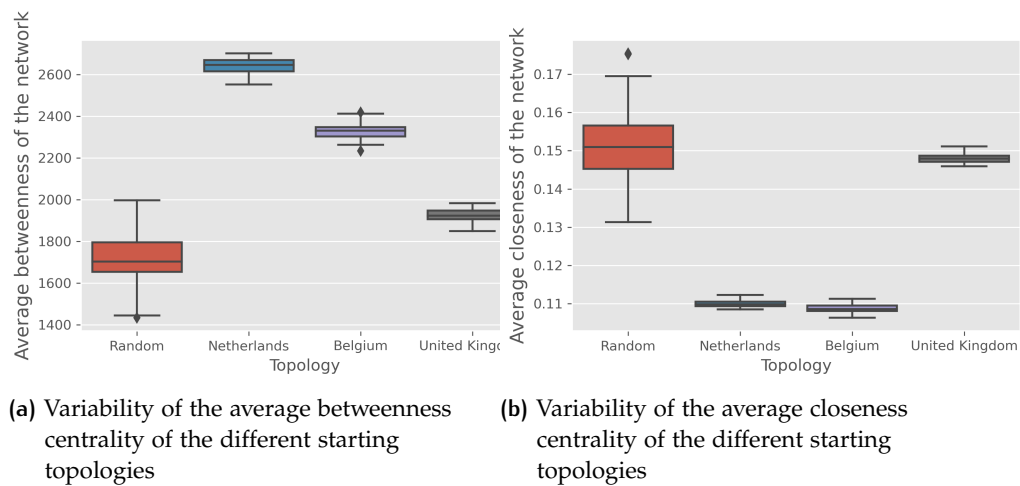


Figure 7.3: Centrality measures for the starting networks in the case of a random topology, a topology based on the Netherlands, Belgium or the United Kingdom

average closeness centrality while the closeness centrality in the topology of the United Kingdom is significantly higher. This can be explained by the fact that the topology of the United Kingdom is orientated from north to south with only horizontal connections in between while the United Kingdom is a much more stretched out country in comparison to the Netherlands and Belgium. In regard to the random topology, there are not that many cross-links, creating a high closeness centrality.

The experiments with the different country topologies aim to explore if there is a stronger link between the centrality measures and the effect of a strategy. Furthermore, concrete insights for the Netherlands, Belgium and the United Kingdom are acquired.

7.6 SUMMERY CHAPTER 7

The setup of six experiments is discussed in this chapter. Based on the results of these experiments, comprehensive strategies based on the costs, hydrogen transition and hydrogen export are constructed. These strategies will then be applied to topologies based on the transmission grid in the Netherlands, Belgium and the United Kingdom. The interpretation of the experiments will be discussed in the next chapter.

In this chapter, the results of the experiments are presented, analysed and interpreted. Based on the results of the individual experiments with the tactics, strategies for minimising the cost and maximising the hydrogen delivery are created, each for a situation with and without an export corridor. These four strategies are then compared. Finally, the strategies are applied to topologies based on the network of the Netherlands, Belgium and the United Kingdom.

8.1 ANALYSIS OF THE INDIVIDUAL TACTICAL OPTIONS

The results of the experiments described in chapter 7 are given, followed by an analysis and interpretation of the results. The focus will be on the expenses of the network transition, the volume of hydrogen delivered in the system, and the volume hydrogen that is exported.

8.1.1 The priority of which pipe to change

Results experiment 1A

This experiment aims to test the five priority options regarding the prioritisation of the network segment to transition, in combination with allowing new pipes or tanks trajectories to be constructed between nodes in the network.

The plots in 8.1 illustrate that for the tactical option where the maximal utility is chosen as a local optimising criterium, the results show higher expenses when new pipes are constructed in comparison to when no new pipes are constructed. In all cases, the expenses are lower when no new pipes are constructed. However, the differences in costs between the scenarios are not significant (appendix H.1). In regard to the volume hydrogen that is delivered, it can be concluded that in the tactical option where the local optimisation is based on utility/cost, and the option to construct a new pipe is given, the highest hydrogen delivery is achieved. This combination is significantly better than other tactics (appendix H.1). In regard to the amount of hydrogen that is exported, no significant differences can be found between the different scenarios (appendix H.1). More detailed plots with the progress over time, and the significance between the different scenarios, can be viewed in appendix H.1.

The biggest network transition occurs for the tactical option when the option for the construction of new pipes is given, and the local optimisation is based on utility/cost. Overall the trend can be seen that for the options

where the construction of new pipes is given, a larger variability is found in the results.

No connection is found between either the average betweenness centrality or the average closeness centrality of the network, and the effect of the tactical options, as shown in appendix H.1.

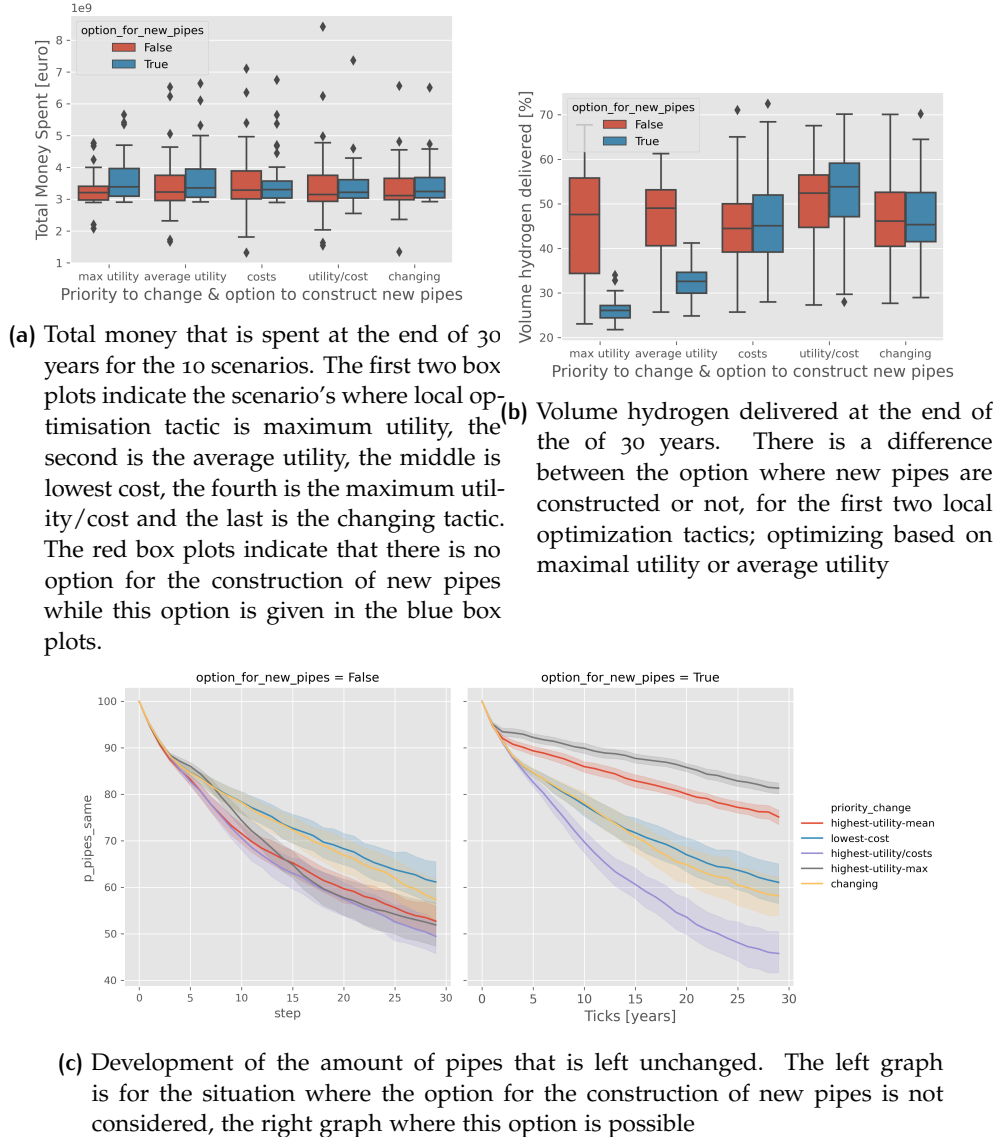


Figure 8.1: Effect of tactical option 1A on the KPI's

Results experiment 1B

The second part of this experiment focuses on the tactical option where the changing priority is applied. In this experiment, different settings are tested:

- In the first scenario, all three tactical options are run for ten years; starting with cost, then utility/cost and finishing with utility. The utility option is based on the average utility.

- In the second scenario, the tactic where the decision is locally optimised based on the lowest cost is not included.
- The third scenario leaves out the utility/cost option, and
- The last scenario starts with the tactic of lowest costs and then moves to local optimisation based on the highest utility/cost while leaving out the option of local optimising based on maximum utility.

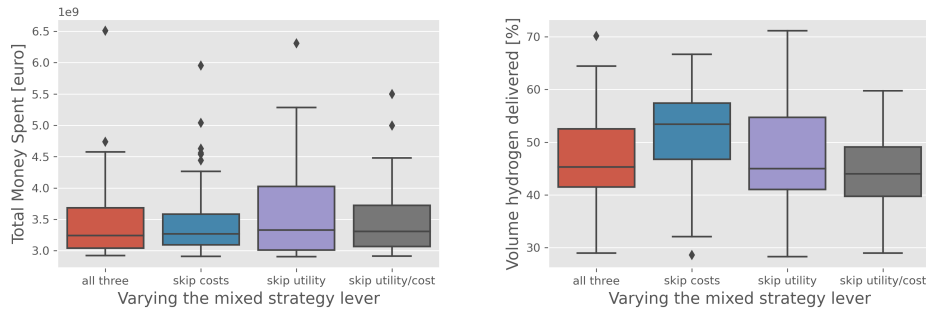
The plots in 8.2 show that the variability of cost in all four scenarios is high, and that there are no significant differences between the four scenarios in regard to the expenses. In regard to the amount of hydrogen delivered, the second scenario has a significantly higher hydrogen delivery than the first and third scenario. The results in 8.4d are in line with the volume hydrogen that is delivered, and changes to the network are needed in order to deliver hydrogen to the customers. How the network changes over time can be viewed in more detail in appendix H.1.

Analysis and interpretation of tactical option 1: The priority of which pipe to change

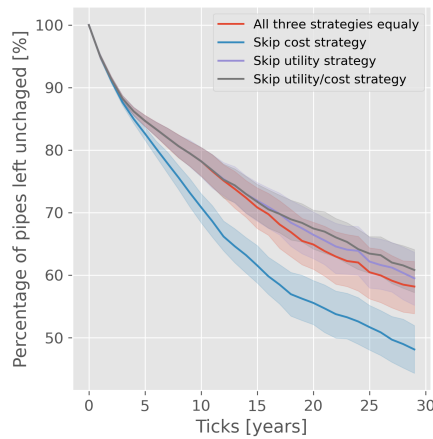
In regard to the best tactic for the local optimisation of the segments to transition, it is best not to choose a tactic that is only based on utility. The local optimisation based on utility will often dictate an option that constructs a new pipe. The costs of new pipes are ten times higher than the costs of changing a pipe. The high costs of the new pipes then consequently have the effect that more of the budget is spent on specific segments; leading to less budget for changes for other parts of the network. With this, only a few, expensive, changes are made instead of a lot of smaller investments that are needed to get to the desired outcome. As a result, it is best to optimise locally with a tactic that includes the cost criterium. This can either be the lowest cost, highest utility/cost, or a mixed tactic.

The transition of the network is path depended. The outcome relies on the tactical choice of the local optimisation criterium. This tactical choice determines which segment is transitioned, and with that, it determines the future decision space. Additionally, the choice of the transition also determines the remaining available budget for that step, and therefore also affects the amount of changes that can be made. The relation between the total expenses of the ten different scenarios to the hydrogen delivery, is visualised in 8.3. This plot contains much information with the hydrogen delivery volume range from 20 to 75%, showing that the results strongly depend on the topology. Even though there is a strong dependence on the topology, the average centrality measures are not a predictor for the effect of the tactical decision (appendix H.1).

If the focus of the network transition is exclusively based on the minimisation of costs, the scenario that minimises costs is based on the tactical option where the option to construct new pipelines is not available, and local optimisation is based on lowest cost. The scenario where the local optimisation is



(a) Total money that is spend at the end of the model run for the four different scenarios where different mixed local optimization options are applied. (b) Volume hydrogen delivered at the end of the model run for the four different scenarios where different mixed local optimization options are applied.



(c) Development of the amount of pipes that is left unchanged over the course of time. The biggest change to the network is in the grey scenario.

Figure 8.2: Effect of tactical options 1B on the KPI's. In the red scenario, the optimization occurs for based on lowest cost, then utility cost and ends with utility; the blue starts with utility cost and then optimized based on utility; the purple starts the local optimization based on cost and then utility; the grey first locally optimizes on cost and then optimizes on utility.

based on utility/cost and the option for the construction of new pipes is possible, also has low expenses. When focusing on the KPI with the objective of maximal hydrogen delivery in the system, the local optimisation should be based on utility/ cost with the option to construct new pipes. These conclusions are derived from the box plots shown in 8.1.

No significant difference can be found within the different scenarios in regard to the hydrogen export. This can be explained with the fact that this tactical option does not focus on hydrogen export and the KPI hydrogen export is not relevant for this strategic option.

Concerning a mixed tactic, the option that first optimises locally based on utility/cost, and then on utility, has the best output in regard to hydrogen delivery. This is in line with the results of experiment 1A, where the highest hydrogen delivery is achieved when the local optimisation is based on util-

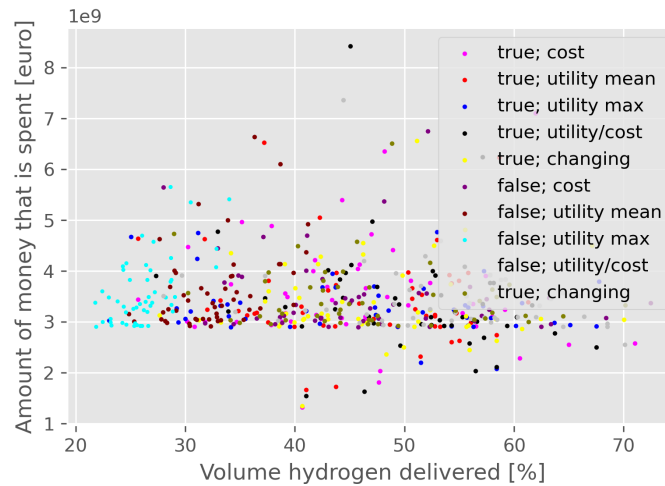


Figure 8.3: Cost in relation to hydrogen delivery for the experiment where different local optimization tactics are examined in combination with the option to construct new pipes or not.

ity/cost.

When comparing this outcome of the mixed tactic with the results of the pure scenarios, the pure scenario where no pipes are constructed, and the optimisation is based on lowest cost, has lower expenses than all mixed scenarios. All mixed scenarios also have a lower hydrogen delivery in comparison to the scenario where the local optimisation is based on utility/cost, and there is an option to construct new pipelines. The mixed tactic does therefore not perform better than the pure tactical options based on the evaluated KPI's.

8.1.2 The effect of an export corridor

Results experiment 2

This second tactical option aims to discover if prioritising the export and import flow of hydrogen and natural gas has an effect on the rest of the network.

From the plots in 8.4 it can be concluded that the total expenses with and without an export corridor are in the same order and there are no significant differences between the two scenarios. Regarding the hydrogen delivery, there is also no significant difference between the two scenarios. This is shown in appendix H.2. Appendix H.2 also provides more insight into the development of two KPI; money that is spent and hydrogen that is delivered over time. Additionally, insight is provided on how the network changes. These plots do not indicate a difference between the two scenarios.

Nevertheless, there is a significant difference between the two scenarios in the amount of hydrogen that is exported, in favour of the export corridor.

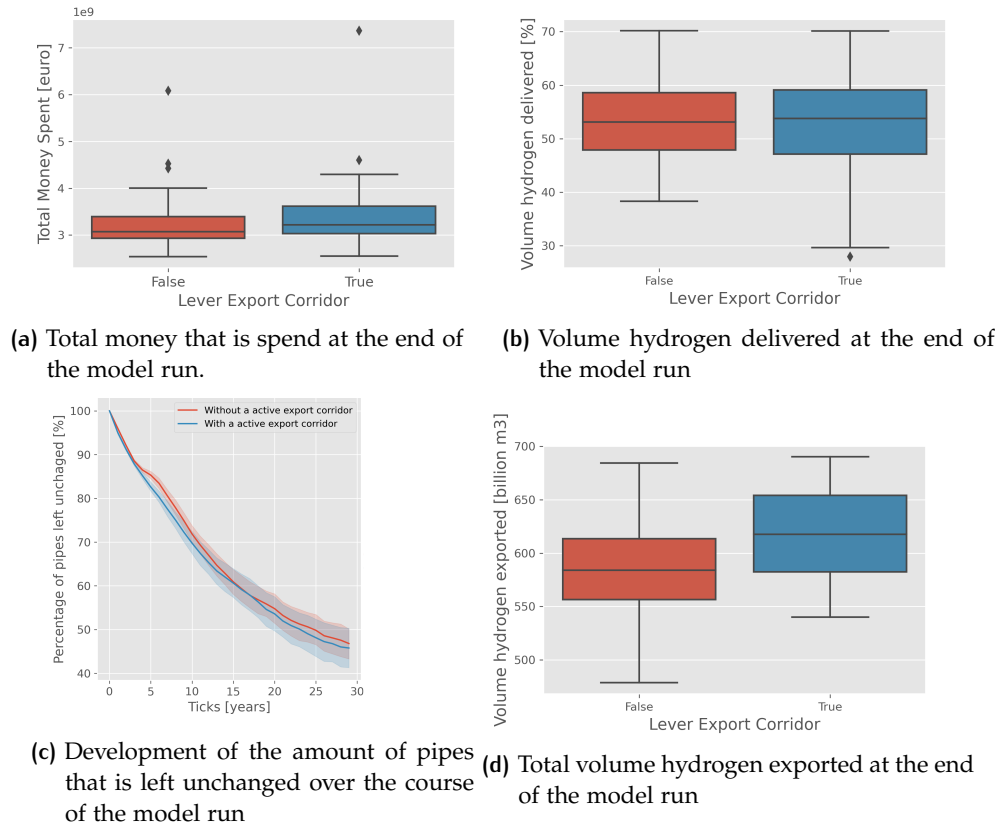


Figure 8.4: Effect of tactical option 2 on the KPI's. The red colour represent the scenario where no priority is given to an export corridor, while the blue colour represent the scenario where the export of hydrogen and natural gas is prioritized.

Analysis and interpretation of tactical option 2: The effect of an export corridor

In regard to the export corridor, the effect of the tactic is minimal, and no difference in the output is proven regarding the expenses and hydrogen delivery within the network. This is confirmed by the scatter plot in figure 8.5. An explanation is that an export corridor is favourable when the hydrogen and natural gas corridor overlap. In this case, essential connections in the network are laid double at the beginning of the model run. The system then benefits from these investments for the rest of the run. However, when there is no overlap, and the natural gas in- and export point scattered, the part of the network that does connects the natural gas import to the natural gas export, is marked essential, and therefore cannot be transferred to hydrogen. Consequently, this can stop the transition of the hydrogen network. Therefore, this tactic is depending on the starting topology of the network. However, this dependence of the topology is not explained by the average betweenness centrality or average closeness centrality (appendix H.2).

The KPI hydrogen export does indicate a significant difference between the two scenarios. This makes sense as in the scenario with the corridor, the first priority of network changes is given to the pipes that connect the hydrogen export points with hydrogen import points. Therefore the connection

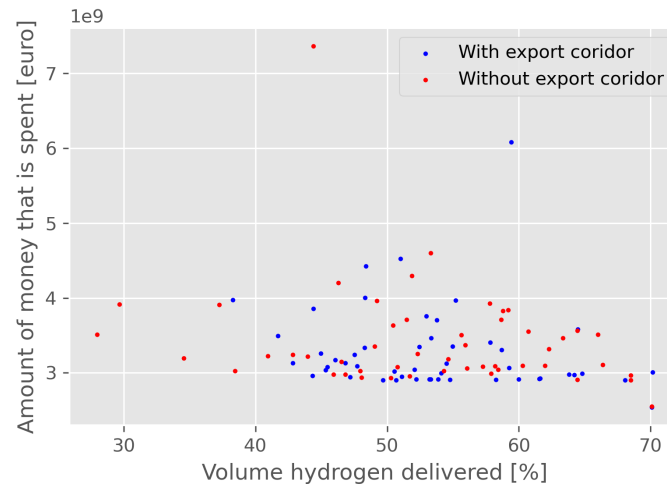


Figure 8.5: Costs in relation to hydrogen delivery for the experiment where a priority is given to import and export connections (blue) or this priority is not granted (red)

between the import and export will be established earlier in time, and the total hydrogen export will be larger.

Nevertheless, the export corridor does not have a significant negative effect on the expenses and hydrogen delivery. Therefore the hypothesis in favour of the corridor will be maintained. For the construction of the strategies, strategies will be constructed with and without the export corridor.

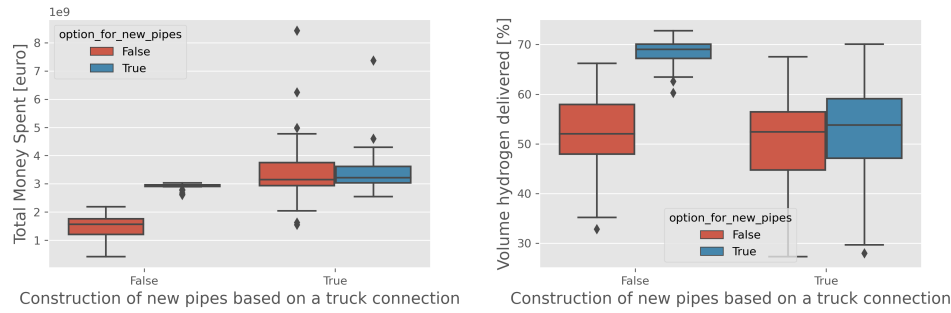
8.1.3 The effect of newly constructed pipelines

Results experiment 3A

The third tactical option reflects on the construction of new pipes. Two different conditions under which pipes can be constructed are evaluated. The first condition is to construct a new pipe when this is the most optimal choice based on the first tactical option discussed previously. The second condition is to allow the construction of a new pipe on a trajectory where a tank delivery was needed more than three times.

The results shown in 8.6, indicate that the expenses are significantly the lowest when no new pipes are constructed. Not constructing pipes on a tank connection reduces the costs the most. The effect on the costs of allowing new pipes or not is limited when tank connections are allowed. The highest volume of hydrogen is transported through the system when no pipes are constructed on tank trajectories, but the option to use new pipes based on an optimal location is possible.

These four different scenarios are similar in the amount of hydrogen that is exported.



(a) Total money that is spent at the end of the model run. (b) Volume hydrogen delivered at the end of the model run.

Figure 8.6: Effect of tactical option 3A on the KPI's. The two box plots on the right represent the two scenarios where no new pipes are constructed based on intensively used tank trajectories. In the two scenarios on the left, on the trajectories where tanks are allocated often, new pipes are constructed. The construction of new pipes based on tank trajectories is not possible in the third and fourth scenario. The red box plots represent the scenarios where the option for the construction of new pipes when this is locally optimised by the system is not allowed. The blue box plots represent the scenarios where the construction of new pipes is based on local optimisation.

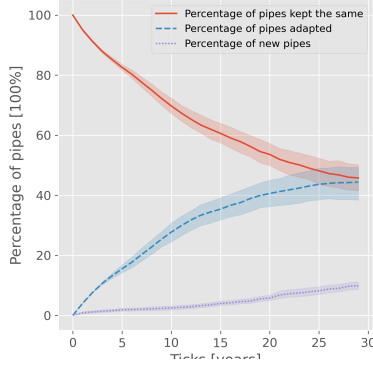
The plots in 8.7 illustrate how the network evolves in all four scenarios. The purple line shows the number of new pipes that are newly constructed. These results indicate that allowing new pipes based on tank connections, significantly contributes to the newly laid pipes, as the increase in figure 8.7b is minimal. In this same scenario, the network has evolved the most. This is indicated by the red line that shows the percentage of pipes in the network that has stayed the same.

Results experiment 3B

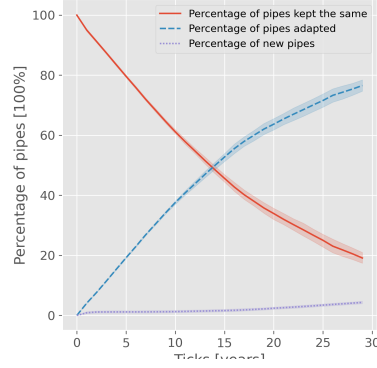
Experiment 3B investigates the situation when a tank trajectory is established and after a period, this trajectory is changed to a pipe trajectory. The tactical option that researched here, is the time duration to after which to construct a new pipe based on a tank trajectory. The results in 8.8 show a significant decrease in costs when the construction of a new pipe based on a tank trajectory is delayed. The trend of the amount of hydrogen delivered is also in favour of delaying the construction. The transition of a tank trajectory to pipelines does not show a significant effect in the hydrogen export.

Analysis and interpretation of tactical option 3: The effect of newly constructed pipelines

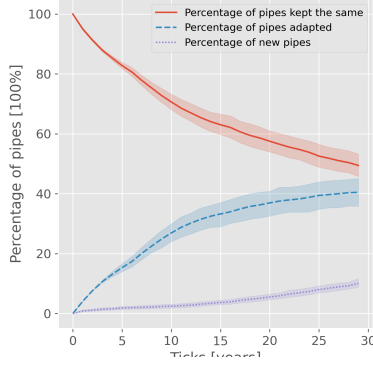
The tactical choice of whether to allow the option to construct new pipes or not, has a significant influence on the behaviour of the system. When strictly looking at costs, it is best not to allow the construction of new pipes. This is intuitive as the costs for a new pipeline are ten times higher than only



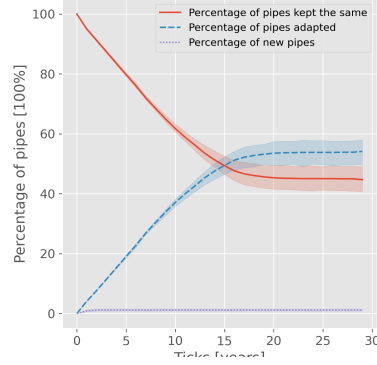
(a) Allowing new pipes for the system to consider when locally optimizing; construct pipes on tank connections



(b) Allowing new pipes for the system to consider when locally optimizing; no pipes on tank connections

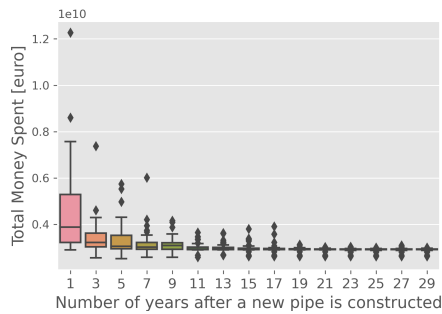


(c) Not allowing new pipes for the system to consider when locally optimizing; construct pipes on tank connections

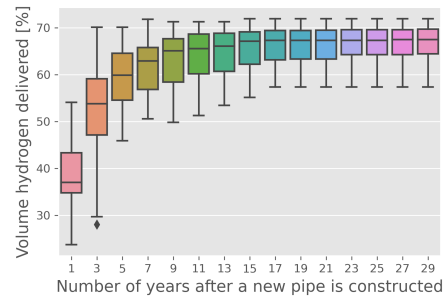


(d) Not allowing new pipes for the system to consider when locally optimizing; no pipes on tank connections

Figure 8.7: Development of the network under the settings of the tactical option 3A. The red line indicates the percentage of pipes that is still the same as the starting situation, the blue line the percentage of pipes that has been changed to be a hydrogen pipe, and the purple line represents the newly constructed pipelines



(a) Total money that is spend at the end of the model run for different scenarios with an increasing time after which a new pipe is constructed on a intensively used tank trajectory



(b) Volume hydrogen delivered at the end of the model run for different scenarios with an increasing time after which a new pipe is constructed on a intensively used tank trajectory

Figure 8.8: Effect of tactical option 3B on the KPI's

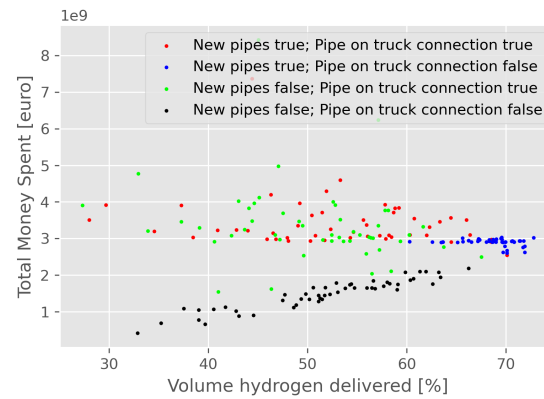


Figure 8.9: Cost in relation to hydrogen delivery for experiment where the effect of the construction of new pipes is considered. 4 scenarios are based on new pipes allowed when the system deems a new pipe to be the local optimal choice (Y/N), or when a tank connection is used intensively (Y/N).

changing an existing trajectory. For the hydrogen transport, this is however not the optimal tactic. In regard to the hydrogen delivery, the tactic where new pipes are constructed based on tank trajectories is unfavourable. However, constructing new pipes when this option is optimised by the system, is beneficial for increasing the level of hydrogen transport. In regard to the expenses KPI, this combination performs second-best.

In the scenario where no new pipes constructed based on a tank trajectory, but the option to include new pipelines in the local optimisation process is given, shows a modest number of new pipelines constructed. Figure 8.7b also shows that these new pipelines are constructed later in time, after approximately 15 years. In the situation where constructing new pipes is not given, which is shown in figure 8.7d, it becomes clear that after 15 years the transition of the network stagnates. Resulting in the fact that the transport of hydrogen also stagnates at year 15. Because nothing happens, there is no need for investments, and this explains the low costs for this scenario. This stagnation of new pipes creates a lock-in for the network and hinders further development, and this should be prevented. The option where it is possible to construct new pipes, allows the network to overcome these lock-ins and evolve further. This can be seen in 8.7b, where the number of changed pipes trajectories continues to increase after 15 years.

In order to minimise costs, no new pipes of any kind should be constructed, and for the maximal hydrogen transport, only new pipes should be constructed when this is optimised by the network itself. The four scenarios and the relation between the costs and hydrogen delivery are visualised in figure 8.9. This scatter plot underlines that the construction of new pipelines based on a tank trajectory is not beneficial, as this will lead to spending significant parts of the budget on inefficient network connections, limiting the budget for other transition options and therefore having a negative effect on

the hydrogen delivery.

The finding that the construction of new pipelines based on tank connections is inefficient, is confirmed by experiment 3B and it shows that both expenses are saved, and more hydrogen is delivered when the duration of a new pipe is construction on a tank trajectory is increased.

The results of these experiments are not susceptible to the average betweenness and closeness centrality of the network. The figures in appendix H.3 clearly how distinct layers are visible and that a scenario performs the over the different range of the two centrality measures.

8.1.4 The effect of budget allocation over time

Results experiment 4

The fourth tactic looks at the effect of different ways to spend the total budget over the years. The results in 8.10 show a significant difference in the expenses between the scenario where the budget is allocated in an increasing manner, and the scenario where the budget is allocated in a decreasing manner. The amount of hydrogen delivered is largest in the scenario where the largest investments are made in the beginning; the decreasing scenario. In this scenario, the largest part of the network is changed. In this same scenario, the hydrogen export is also the largest. The differences between the scenarios and the significance of the differences, together with how these KPI's progress over time, are shown in appendix H.4.

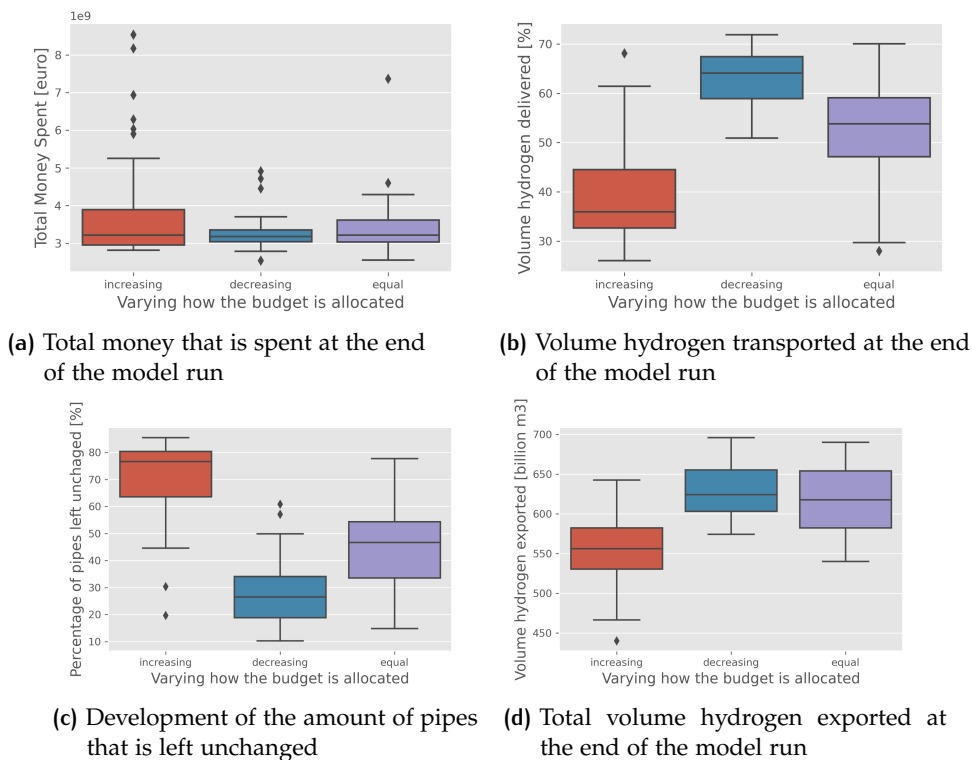


Figure 8.10: Effect of tactical option 4 on the KPI's

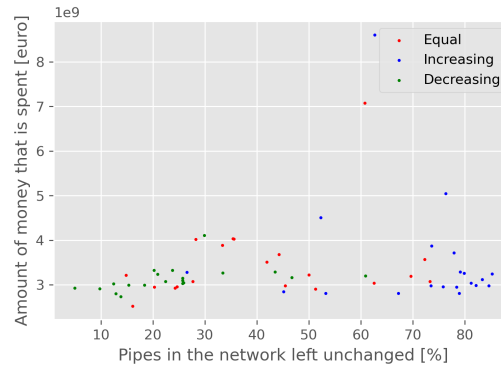


Figure 8.11: Cost in relation to hydrogen delivery for the different tactic options for budget allocation

Analysis and interpretation of tactic option 4: The effect of budget allocation over time

The results presented in figure 8.10 prove that the largest part of the budget should be spent at the beginning of the transition, and the hypothesis is therefore confirmed. With a significant initial investment, critical paths can be constructed early on in the transition, and the system can benefit longer from these investments. These results are underlined in the scatter plot, shown in 8.11. Three distinctive clusters can be found representing the three different scenarios. This indicates that this tactic is not that sensitive to the starting topology of the system. Consequently, no effect between the centrality measures explored and the KPI's are found, as described in appendix H.4.

8.2 CONSTRUCTION AND ANALYSIS OF THE STRATEGIES

Based on the individual tactics, best practices for the lowest costs and the highest hydrogen delivery are defined. Since most tactics, except the tactic that prioritises the flow of import and export, and the tactic that considered the budget allocation over the years, do not have a significant effect on the volume hydrogen exported, no strategy is constructed based on this KPI. However, given that an export corridor does not influence results in regard to the costs and hydrogen transport, both options in this tactic are incorporated for the strategy based on costs and hydrogen delivery. With this, four comprehensive scenarios are constructed. The settings for these four scenarios are represented in table 8.1.

Strategy	Number	Option for new pipe	Priority change	Time between strategies	Corridor	New pipe on tank connection	Time to construct a pipe	Budget allocation
Costs with corridor	1	False	lowest cost	-	True	False	-	Decreasing
Hydrogen with corridor	2	True	high utility/cost	-	True	False	-	Decreasing
Costs without corridor	3	False	lowest cost	-	False	False	-	Decreasing
Hydrogen without corridor	4	True	high utility/cost	-	False	False	-	Decreasing

Table 8.1: Overarching scenarios and their settings

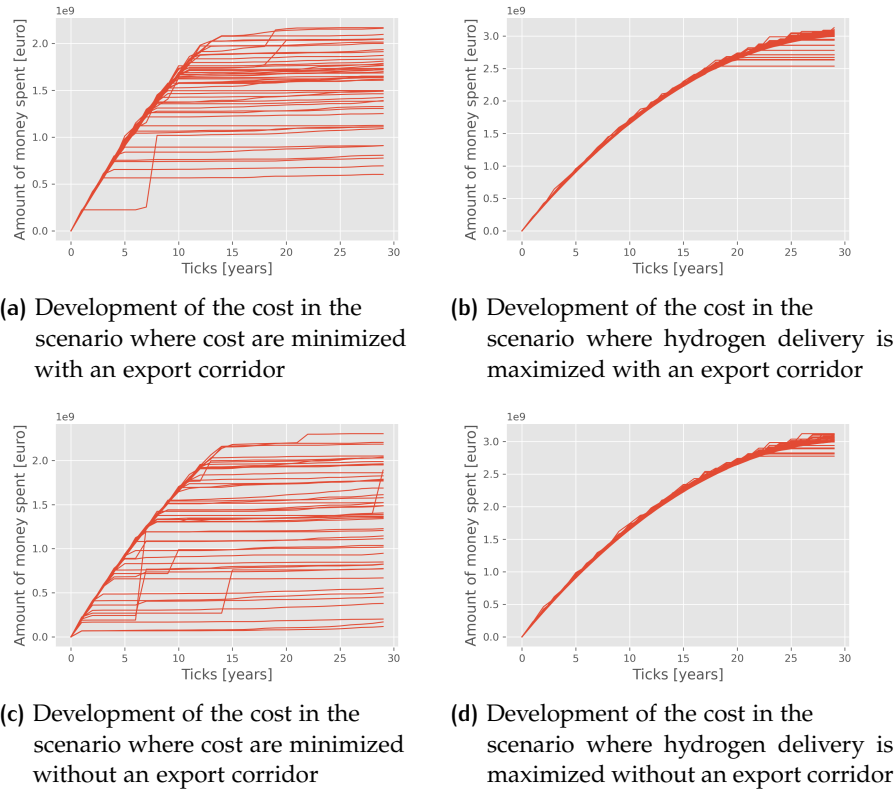


Figure 8.12: Development of the cost in the four overarching scenarios over time

In regard to the expenses over time, a big difference between the scenarios can be observed. The plot in 8.12 illustrates how many lines run out horizontally in the scenarios where the minimalisation of costs is the driver behind the strategy. This behaviour starts between 4 and 15 years with an export corridor, and between 0 and 15 years without an export corridor. This behaviour indicates that there are lock-ins in the evolution of the network, and no further process occurs. The export corridor ensures that these lock-ins occur slightly later in time. The strategies where a high volume of hydrogen delivered is the driver, show little lock-in effect, relatively late in the transition process.

The variety of the different runs in the strategies where cost are minimised, is very wide. In contrast, the variety of the cost in the strategies where the hydrogen delivery is maximised is limited. This indicates that the cost-based strategies are more sensitive for the starting topology, while the strategies for maximisation of hydrogen delivery are not.

The behaviour described above is also confirmed by the plots showing the development of the hydrogen delivery. These results are shown in appendix I.1.

In regard to the transition of the network, significantly more pipes are adapted in the strategies where the hydrogen delivery is maximised. As described before, in the strategies where costs are minimised, lock-ins occur.

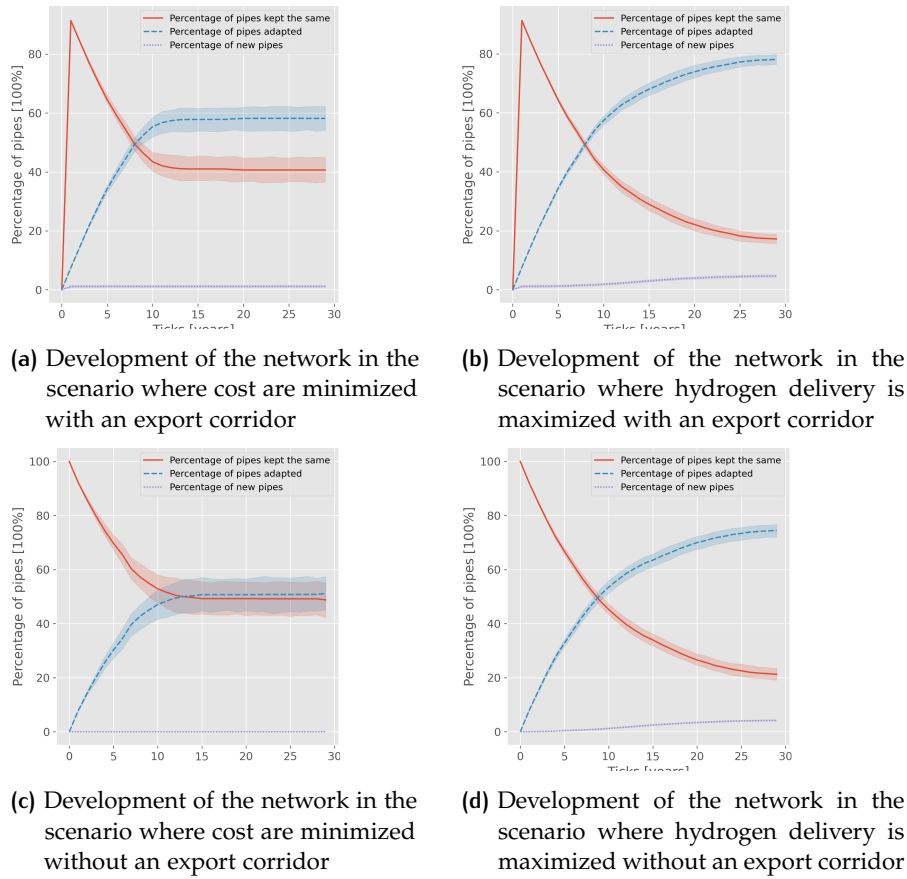


Figure 8.13: Development of the network in the four overarching scenarios

These lock-in effects are also visual in plots 8.13, where the progress of the network is visualised.

In conclusion, in total, 42 scenarios have been examined. The first 38 scenarios were intended to test the effect of different tactics. Based on these results, four comprehensive strategies based on the cost, the hydrogen delivery and the hydrogen export were constructed. In these comprehensive scenarios, the strategy perform best on the criterium they were constructed on. This indicates that there are no unexpected interactions between the strategies. The implementation of the hydrogen corridor does results in higher expenses, as the system makes connections it otherwise might not make when comparing the costs-based strategies. These differences are significant (appendix I.9). The corridor also leads to a higher hydrogen delivery in the system for these costs-based strategies, as the system can benefit from early network changes. However, the difference between the strategy based on the maximisation of hydrogen delivery, with and without an export corridor, are not significant for total expenses and hydrogen delivery. The output of all the scenarios is combined in table 8.2. The settings of all scenarios can be reviewed in appendix G.

Experiment	Scenario	Money spent [billion €]	H ₂ delivered [%]
1a	1	3,51	46,2
1a	2	3,65	32,7
1a	3	3,60	26,2
1a	4	3,43	53,0
1a	5	3,47	46,8
1a	6	3,30	45,4
1a	7	3,43	46,6
1a	8	3,52	46,3
1a	9	3,38	50,3
1a	10	3,36	46,9
1b	11	3,47	46,8
1b	12	3,49	51,7
1b	13	3,59	46,8
1b	14	3,51	44,5
2	15	3,43	53,0
2	16	3,29	53,5
3a	17	3,43	53,0
3a	18	2,90	68,5
3a	19	3,38	50,3
3a	20	1,49	51,8
3b	21	4,51	38,8
3b	22	3,43	53,0
3b	23	3,33	59,3
3b	24	3,18	61,7
3b	25	3,12	63,3
3b	26	3,00	64,4
3b	27	2,99	65,0
3b	28	2,98	65,8
3b	29	2,96	66,3
3b	30	2,92	66,3
3b	31	2,92	66,3
3b	32	2,91	66,5
3b	33	2,91	66,5
3b	34	2,91	66,5
3b	35	2,91	66,6
4	36	3,43	53,0
4	37	3,79	38,7
4	38	3,27	63,0
Costs with corridor	39	1,56	53,7
Hydrogen with corridor	40	2,97	69,5
Costs without corridor	41	1,35	39,8
Hydrogen without corridor	42	3,01	66,8

Table 8.2: Output of all the scenarios

8.3 THE EFFECT OF THE STRATEGIES ON STARTING TOPOLOGIES BASED ON THE NETHERLANDS, BELGIUM AND THE UNITED KINGDOM

8.3.1 The effect of the network on the strategies

In this section, the four strategies are explored by applying them to a topology based on the Netherlands, Belgium and the United Kingdom.

Strategy 1: Minimise cost, prioritise the export of hydrogen and natural gas

The boxplots in figure 8.14 show that the effect of strategy 1 is different in the four different settings of the starting topology, as the four different topologies show differences in the outcome. In the case of the random topology and the topology in Belgium, lock-ins occur. This conclusion is drawn as the total hydrogen delivery is limited, and as the development of costs stagnates (appendix I.2). The starting topology based on the UK shows a wide variety, where in some cases lock-ins occur. However, these lock-ins are less extreme than in the starting topology based on Belgium and the random starting to-

pology. In appendix I.2 the progress of the KPI's overtime is given. These graphs indicate that in the topology based on the Netherlands, the lock-ins occur between 12 and 15 years, while the lock-ins in Belgium start between 2 and 12 years. For the situation in the UK, the majority of the lock-ins occur between 8 and 15 years.

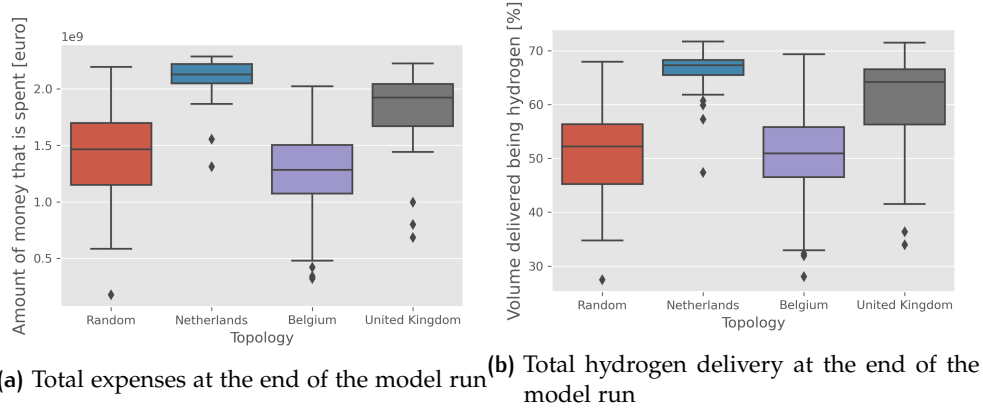


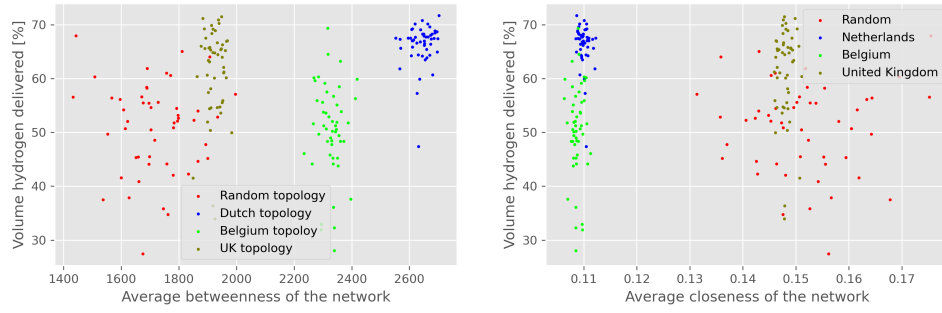
Figure 8.14: The effect of the strategy 1; minimal cost with an export corridor on the total expenses and hydrogen delivery for four different starting topologies

No relation is found between the betweenness centrality or the closeness centrality of a starting topology in relation to the susceptibility to lock-ins of a network. The scatter plots in figure 8.15 show that the topology based on the Dutch network has the highest average betweenness and that this leads to the highest hydrogen delivery. However, the hydrogen delivery in the starting topology based on Belgium is lower than the hydrogen delivery in the UK, while the betweenness centrality in the starting topologies based on the UK is lower than in the starting topologies based on the Belgium gas grid.

In regard to the closeness centrality, the average closeness centrality in the topology based on the Netherlands is similar to the average closeness centrality in Belgium, however, as described before, there is a significant difference between the effect of strategy 1 in these two countries.

Strategy 2: Minimise cost, no prioritisation of the export of hydrogen and natural gas

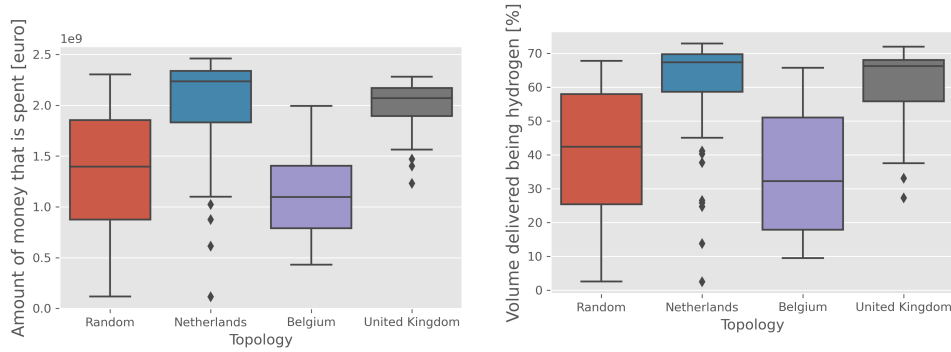
The boxplots in figure 8.16 show that the effect of strategy 2 is different in the four different settings of the starting topology, as the four different topologies show differences in the outcome. The same effect as the effect of strategy 1 can be observed. However, the spread of the results in this strategy is wider than in strategy 1. This can be traced back to the fact that if an export corridor is prioritised, the priority of the export corridor ensures the same transitions at the start of the network transition, while the transition process without a corridor is not shaped by priorities.



(a) The relation between the hydrogen delivery in the system and the average betweenness centrality of the starting topology (b) The relation between the hydrogen delivery in the system and the average closeness centrality of the starting topology

Figure 8.15: The relation between the centrality of a topology and the volume hydrogen that is delivered for strategy 1

In regard to the centrality measures, the same results are observed. The scatter plots for strategy 2 are presented in appendix I.3.



(a) Total expenses at the end of the model run (b) Total hydrogen delivery at the end of the model run

Figure 8.16: The effect of the strategy 2; minimal cost without an export corridor on the total expenses and hydrogen delivery for four different starting topologies

Strategy 3: Maximise hydrogen delivery, prioritise the export of hydrogen and natural gas

The boxplots in figure 8.17 show that the effect of strategy 3 is different in the four different settings of the starting topology, as the four different topologies show differences in the outcome. This strategy leads to fewer lock-ins, and in all topologies, the hydrogen delivery is significantly higher compared to the first two strategies. The hydrogen delivery in the three countries is in the same range, while the expenses differ a lot.

The relation between the expenses and hydrogen delivery is made visual in figure 8.18. This figure indicates that for the random topology, the costs are always relatively high, while there is a big range in the hydrogen delivery. In the starting topologies based on the countries, the hydrogen delivery

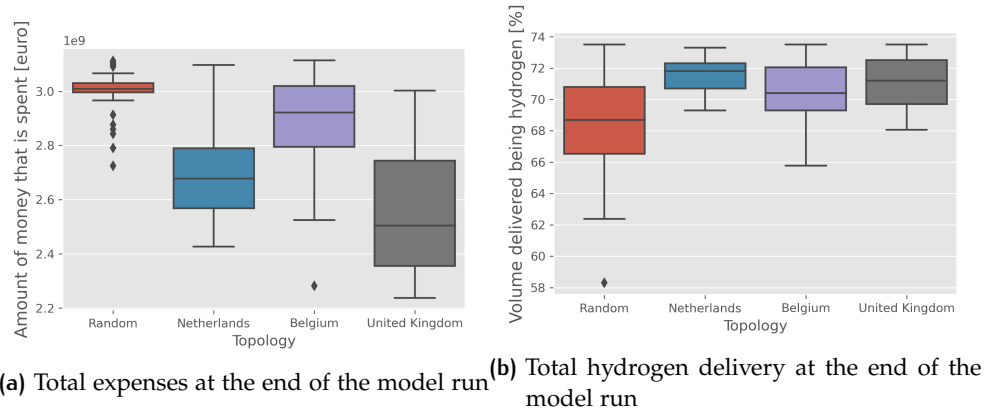


Figure 8.17: The effect of the strategy 3; maximal hydrogen delivery with an export corridor on the total expenses and hydrogen delivery for four different starting topologies

mostly ranges between 69% and 74%. In this cluster, it is visual that most green dots, representing the Belgium based topology, show the highest expenses, while it is evident that the brown dots, representing the topology based on the UK grid, show the lowest expenses.

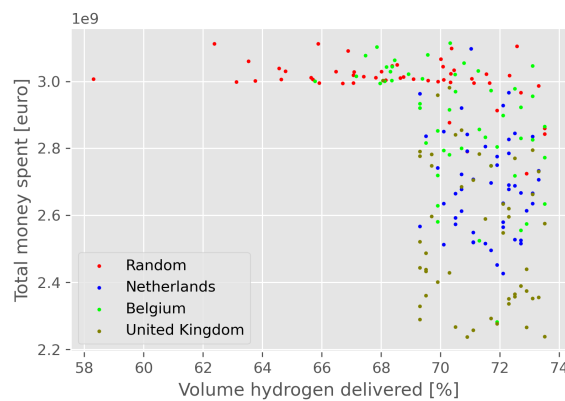
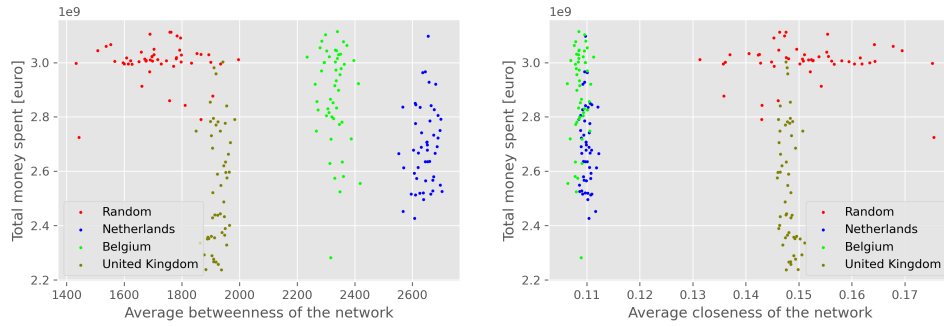


Figure 8.18: The relation between expenses and hydrogen delivery in strategy 3

The scatter plots in figure ?? show the relation between the cost and the centrality measures. From figure 8.18 it can be said that this strategy has the best effect on a starting topology based on the UK, followed by a Dutch based starting topology. In the random topology, the highest expenses are made despite a broad (and lower) range of hydrogen delivery in comparison to the country-based topologies. Nevertheless, this distinct sequence in the effectiveness, cannot be observed in combination to the average centrality measures of the network topologies.

Strategy 4: Maximise hydrogen delivery, no prioritisation of the export of hydrogen and natural gas

In comparison to strategy 3, strategy 4 mainly affects the random topology, where the spread of the hydrogen delivery is lower, and the volume is higher.



(a) The relation between the hydrogen delivery in the system and the average betweenness centrality of the starting topology (b) The relation between the hydrogen delivery in the system and the average closeness centrality of the starting topology

Figure 8.19: The relation between the centrality of a topology and the expenses that is made for strategy 3

The boxplots showing the effect of this strategy to maximise hydrogen delivery without an export corridor, on the total expenses and hydrogen delivery for four different starting topologies are presented in appendix I.5. This difference for the random starting topology is visual when comparing the scatter plot of figure 8.20 with the scatter plot in figure 8.18.

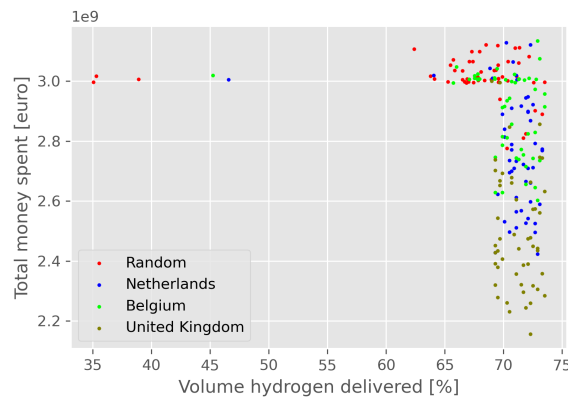


Figure 8.20: The relation between expenses and hydrogen delivery in strategy 4

Similar to strategy 3, no relation between the centrality measures and the performance of strategy 4 is observed.

8.3.2 Country specific analysis

The topology based on the Netherlands

In the starting topology that is based on the Dutch gas infrastructure, strategy 2, which focuses on costs minimisation without an export corridor, leads to the lowest expenses. However, this is at the expense of the volume of hydrogen delivery. Strategy 1, that also focuses on cost minimisation, but with an export corridor, has a significantly higher volume of hydrogen delivery than strategy 2. Strategy 3 and strategy 4 are comparable in regard to the expenses. However, significantly more hydrogen is exported in strategy 3,

where the export corridor is active. There are similarities between strategy 3 and 4 and strategy 1. It can be deduced that there are some situations where costs can be saved, while the hydrogen delivery remains high. These results indicate that strategies 1, 3 and 4 can possibly lead to the same point in regard to expenses and hydrogen delivery. However, the likeliness to get to that point is higher for strategy 3 and 4. Consequently, the Dutch based starting topology with its exact location of nodes has an influence on how a strategy unfolds. The significant values between the strategies can be found in appendix I.6

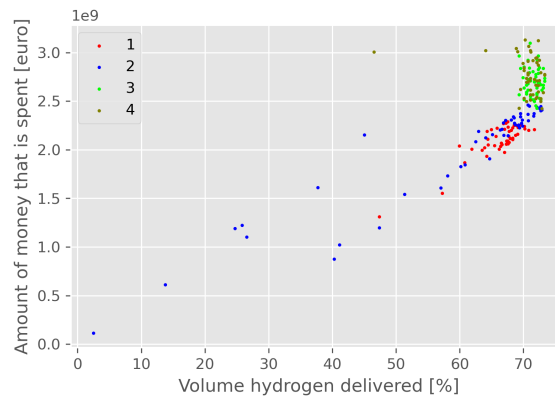
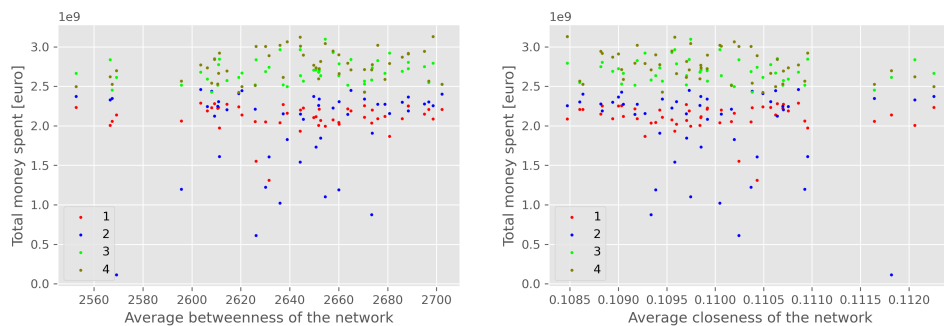


Figure 8.21: The relation between expenses and hydrogen delivery in for the four different strategies in the topology based on the Dutch gas infrastructure

The result of these strategies are independent on the average betweenness- and closeness centrality, as can be concluded from figure 8.22 where clear layers can be found along the spectrum of the centrality measures. The betweenness centrality and closeness centrality are therefore not an indicator that can be used to predict the effectiveness of the four created strategies.



(a) The relation between the expenses and the betweenness centrality **(b)** The relation between the expenses and the closeness centrality

Figure 8.22: The relation between expenses and centrality measures in for the four different strategies in the topology based on the Dutch gas infrastructure

The topology based on Belgium

For the starting topologies based on the Belgium gas network, a distinct cluster of strategy 3 and 4 can be found in the upper right corner of figure 8.23. These two scenarios have significantly higher expenses, but also a significantly higher hydrogen delivery than strategy 1 and 2. Strategy 1 and 2 have a similar range of expenses; however, the hydrogen delivery is higher in strategy 1. In Belgium, a deliberate trade-off needs to be made between the expenses and the hydrogen delivery. This is different from the situation based on the Dutch gas network, where, in a few cases, the same outcome could be reached by all four strategies.

Similar to the topology based on the Netherlands, no relation is found between the centrality measures and the effectiveness of the strategies.

The significant values between the strategies, and the scatter plots for the centrality measures, can be found in appendix I.7.

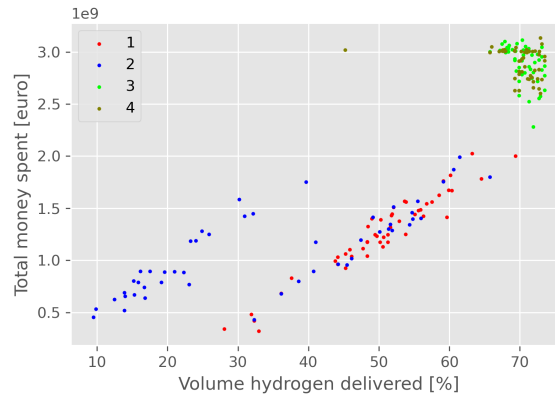


Figure 8.23: The relation between expenses and hydrogen delivery in for the four different strategies in the topology based on the Belgium gas infrastructure

The topology based on the United Kingdom

Strategy 3 and 4 lead to the highest hydrogen delivery in the topology based on the United Kingdom. Similar to the Dutch-based topologies, there is a similarity between strategy 3 and 4 and strategy 1. This indicates that there are some situations where costs can be saved, while the hydrogen delivery remains high.

The effect of the strategies in the scenarios based on the Dutch infrastructure and the infrastructure based on the United Kingdom are comparable. Similar to the topology based on the Netherlands, no relation is found between the centrality measures and the effectiveness of the strategies. The similarities between the two countries cannot be traced back to the two studied centrality measures. As shown in figure , the average betweenness centrality and closeness centrality are significantly different in the starting

topologies based on the Netherlands and the United Kingdom.

The significant values between the strategies, and the scatter plots for the centrality measures, can be found in appendix I.8.

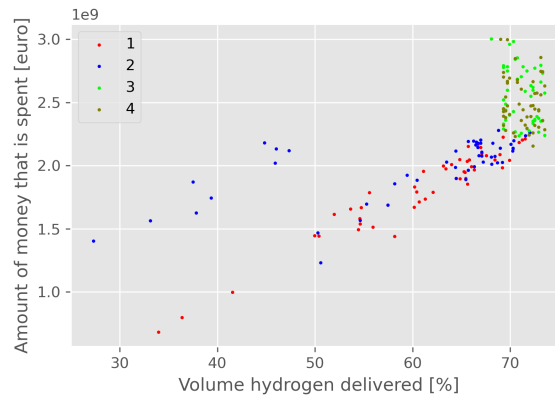


Figure 8.24: The relation between expenses and hydrogen delivery in for the four different strategies in the topology based on the gas infrastructure in the United Kingdom

8.4 VALIDATION

Traditionally, validation is focused on the accuracy of the representation in the model in comparison with the real-world system it represents (van Dam et al., 2013). However, this model is constructed to uncover insights into the transition of a network, and there is no real world system to compare this model to.

Sargent (2010) however, describes that the validity of a model should be determined with respect to the purpose for which the model was developed. In order to determine this, the model's output variables should be defined, and the results should be in an acceptable range of accuracy. This range of accuracy is then again connected to the purpose of the model.

The purpose of this model is to evaluate the transition from a natural gas infrastructure to a hydrogen infrastructure under the influence of different strategies. The model shows the transition from a completely dominated natural gas network to a (partial) hydrogen network and the steps it takes to get to the end state. There are four different tactical options which can be altered. The strategies can be constructed by looking at the effect of the individual tactical options. With this large option space, strategies can be constructed.

In regard to the input of the model; the location of the nodes, the demand/supply of the nodes and the readiness for hydrogen, many assumptions and generalisations are made. For this reason, the accuracy of this model is not specific to predict the actual progress of the transition and the exact results on the KPI's. The effect of strategies on system-level, however, is shown, and that is in the range that is acceptable for the purpose of this

model; determining if there is a significant effect of the tactics and strategies and whether this effect is positive or negative in relation to the evaluated KPI's.

The total costs, the volume hydrogen that is delivered within the network, the percentual change of the network and the volume hydrogen that is exported are the KPI's that are evaluated. Because of the high correlation between the volume hydrogen delivered and the percentual change of the network, the last is not considered in the construction of the strategies. The results of the tactics indicated that there often was no significant difference for the volume hydrogen that was exported, with the exception of the tactic where the effect of the export corridor was investigated. For this reason, the strategy based on costs and hydrogen delivery both are constructed with and without an export corridor. The consideration for constructing strategies based on costs and based on hydrogen delivery is made to indicate how specific strategies influence the transition of the hydrogen network. More nuanced strategies would not reflect on the KPI's as strong, and it would be more challenging to trace back the effect of a strategy to the specific setting in the strategy. The obtained insights would therefore be less strong and would not meet the purpose of this model as well as the current strategies do.

It can be stated that the order of magnitude of the results is in the correct range. This model is constructed based on the Dutch system. The total length of the transmission network is calibrated to the length of the transmission network of the Netherlands. Additionally, the length of the Dutch distribution grid is included in the links that connect the distribution sink nodes to the transmission grid. When running the model, the different scenarios have different total expenses as a result. The results in table 8.2 indicate that the costs range between 1.56 billion euro and 3.98 billion euro. This order of magnitude is confirmed by [van der Walle \(2020\)](#) in the NRC and by [Gasunie \(b\)](#). [van der Walle \(2020\)](#) estimated the expenses for the transition of the network and expenses for the storage to be between the 1.3 and 3 billion euro. The report of [Gasunie \(b\)](#) stated that about 1.5 billion euro is needed to create a viable hydrogen infrastructure. Although the expenses of this model are slightly higher, they seem in range.

Furthermore, extreme value testing and sensitivity analyses are performed to uncover if the system behaves as is expected. The outcomes of these analyses indicate that the system behaviour is adequate. A full description of the analyses can be found in appendix J.

8.5 SUMMERY CHAPTER 8

The effect of the different tactical options, which were tested in the experiments, are presented and interpreted in this chapter. After constructing strategies based on the outcome of the experiments with the tactical options, and applying these strategies to country-specific topologies, an answer is given to the third sub-question; 'What are the effect of transition strategies for the transition path towards a hydrogen infrastructure?'.

The first tactical option aimed to examine what criterium the local optimisation process should use. If the aim is to minimise cost, no new pipes should be constructed, as they are very expensive, and the local optimisation criteria based on costs. To generate a maximal hydrogen delivery in the system, the model shows that the option for new pipes should be given, and the choice what pipes trajectory to change should be based on utility/cost.

In regard to an export corridor, this does not significantly affect the cost and the total volume of hydrogen transportation. The volume of hydrogen export, however is significantly higher with an active corridor.

The construction of new pipes is needed to overcome lock-ins. The new pipes should be constructed through the local optimisation process.

The largest part of the budget for the new hydrogen infrastructure should be spent at the start of the transition process, allowing the system to benefit from early investments longest.

Four strategies are constructed based on the results of the tactical options.

- Strategy 1: the minimisation of cost while applying an export corridor;
- Strategy 2: the minimisation of cost without an export corridor;
- strategy 3: the maximisation of the hydrogen delivery while applying an export corridor and
- strategy 4: the maximisation of the hydrogen delivery without an export corridor.

In both strategy 1 and 2, a significant lock-in effect arises. Lock-in effects keep the expenses low, however the transition of the hydrogen network stagnates, and this negatively affects the volume of hydrogen transport in the system.

The lock-in effect is also found to some degree when applying the strategies to topologies based on the Netherlands, Belgium and the United Kingdom. The lock-in effects of strategy 1 and 2 are less present in the topologies based on the Netherlands and United Kingdom compared to the random topology tested and the topology based on Belgium. The high costs corresponding to strategy 3 are significantly mitigated in the topology based on the United Kingdom, but also lower for the topology based on the Netherlands.

In the next chapter, the results will be reflected upon. Additionally, the limitations of the study are discussed, and the results are generalised for real-world situations.

9 | DISCUSSION

9.1 LIMITATIONS OF THE STUDY

This section discusses some of the critical assumptions that were made based on the effect of these assumptions on the results. Subsequently, the limitations of the model are discussed, as well as the generalizability of the results.

9.1.1 Critical assumptions

This section reviews several assumptions based on the impact on the outcome of the study. The complete list of all assumptions made in this thesis can be found in [appendix C](#).

The first critical assumption is that in this model, the demand is leading. With this, the assumption is made that there will always be enough supply to meet this demand. As indicated in [table 4.1](#), there is a gap between the current hydrogen production and the potential hydrogen demand. There is a lack of information on the development of hydrogen production leading to this assumption. In this thesis there is a focus on the network transition and not the hydrogen generation and the possibilities here. If a limited hydrogen production were included, the model would have a whole new dimension with elements of competition. In such a case, the development of the hydrogen network would be much more focused on the location of the hydrogen source nodes. The hydrogen network would evolve, and whenever a sink node is attached, the demand of this sink node would be deducted from the capacity of the hydrogen source node where the network is linked to. Other roll-outs of hydrogen networks would evolve from other hydrogen source nodes, and this evolution would come to a halt whenever all the hydrogen from a source node is consumed. Consequently, the network transition pace would completely depend on hydrogen production sites, and a scarcity of hydrogen would slow down and potentially stop the transition. In the Netherlands, the current hydrogen production is 13 billion m³, and the potential demand is 55 billion m³. This means that if the hydrogen production would not be increased, only 23,6% of the demand can be met. Accordingly, this would result in sink nodes in the proximity of a hydrogen production source node to be provided with hydrogen, and nodes further away would not be connected to the hydrogen infrastructure, and therefore would not be part of the transition. Subsequently, the effect of the randomness of the topology would gain weight, as this randomness is based on the location of the nodes. However, it is questionable whether this is accurate or not. If the decision who receives hydrogen is decided politically, there would be no natural net-

work transition as described in this thesis. The infrastructure would follow the top-down sequence that is determined outside the decision space of the model.

With a cap on the hydrogen transport, the strategies that focus on a higher hydrogen delivery, while potentially leading to higher costs, are less likely to occur, as the full potential of these strategies will not be reached. With a cap on the hydrogen production, the trade-off between including an export corridor or not will increase, as the choice needs to be made between fulfilling domestic demand or maintaining the international position of a transit country. This last choice needs to be made outside the scope of this model.

The second assumption considers the demand (and therefore supply) to be constant over time. This assumption is a considerable simplification in comparison to the real-world situation. By increasing utility scores in time, and having utility score starting at different time points, this model tries to mimic the actual real-world behaviour. However, this is only a part of the utility score, and the factor of growing demand is not fully included. If this assumption would not have been made this way, it is likely that the number of options for the development of the hydrogen network would be more limited at the start of the model run, and the number of options would gradually increase over time.

With an increasing demand over time, there is a chance that investments in the network at an earlier stage would be too small, and therefore more lock-ins would be created when demand rises later.

Another risk is that the demand in certain regions is not foreseen and therefore, the regional infrastructure does not have the possibility to transition in time to satisfy that regional demand. In real life, demand would probably show a growth pattern over time, with a transition that needs to precede that. This means that most that weight would be shifted towards the end, and the tactic that allocates the budget increasingly would now be more opportune. This is different from the finding in the current model, where it is favourable to invest the most at the start of the transition. Within the tactical options, a mixed local optimisation; where the beginning of the optimisation is based on cost, but this later is changed to optimisation based on utility or utility/cost, is likely to be realistic for the system, as this would anticipate more on the increasing demand. With the likeliness of a different tactical decision for the local optimisation, the strategies that are formed based on these tactical decisions will probably include this mixed strategy for a better outcome.

A third assumption regards the capacity of the pipes. This assumption is based on Gasunie's communication that the current natural gas infrastructure would have enough capacity to be used for the hydrogen ambitions. For this reason, the added complexity of the capacity of pipes was not included in the model.

If capacity had been an issue, the location of source nodes would gain importance for the transition of the network. If for instance a couple of source nodes would be located in close proximity to each other, and the pipe that connects that area of the network with an area where no source nodes are

located, this pipe could be a limiting factor for the transition of the hydrogen network. Consequently, the need for the construction of new pipes would increase to overcome this limiting factor, and with it, the chance for lock-ins. As a result, more budget is allocated to new pipes, hindering the overall evolution of the network. The effect of the starting topology would be increased without this assumption. In the two strategies that focus on the maximisation of hydrogen delivery, the option to construct new pipes is included. These two strategies will therefore remain unchanged. The two strategies that minimise the expenses, however do not include the option to construct new pipes. With a more significant risk of lock-ins, the effect would be that the lock-ins occur even faster, resulting in a lower hydrogen delivery and lower expenses, as the evolution of the network would stagnate earlier. The effect of the export corridor in the strategies will also become more significant, as early on, a part of the capacity of the grid will be reserved for international gas transport.

The fourth assumption is not to represent the network in this research as a double network, as is the situation in the Netherlands. With this assumption, there is an increased dependence on the topology, and with this, a bigger chance for lock-ins. In a double network, there is always the option to provide areas that are laid double with both gas types. Due to the large implication of this assumption, it is not possible to precisely predict the results of the tactical options and therefore, the kind of strategies that would be constructed for the Dutch infrastructure. In appendix K, more attention is given to the situation in the Netherlands with a double network. This description is not based on an agent-based model, but a quick calculation. With a double network, need for an evolutionary model is however reduced, and with this, more general insights on network evolution will not be obtained.

9.1.2 Limitations of the model

The first limitation of the model is the way the utility of a pipe is calculated. At this moment, the utility of a pipe corresponds with either the average utility of all the nodes it is connected to or the maximum utility of one of the nodes it is connected to. In this way of calculating the utility of pipes, pipes that connect many sink nodes have a higher utility. This higher utility is partially compensated by the other factors that determine the utility score, such as the distance between a node and the hydrogen node that is closest. As sink nodes are always located at the end of the network, the distance to a hydrogen point is further. Nonetheless, a greater value of some, especially connecting, pipes is not recognised by this model. An improvement would have been if the pipe utility grasped more than only the utility of its neighbouring nodes. An option would be to base the utility of a pipe on the increase of the utility of the entire system when the pipe in question would be changed or added. For every step where there is still budget available, the gain for the entire system for every pipe transition option should be calculated. The local optimisation should then be based on this utility,

utility divided by cost or other optimisation criteria. The computing complexity and demand to assess this for the complete network would however be enormous, as this needs to be done for the entire network in every step of the transition. This option was therefore not possible in the time frame of this master thesis.

The second limitation also relates to the utility score and how it is build-up for the sink nodes. The utility score is a combination of starting value, which is related to the sector the node represents, and a representation of the assurance for investment as an interaction between the network and the node. In this first part, values are assigned for:

- the value where the utility start from,
- with how much the utility score increases every year and
- the year when this increase starts.

Information is found on how the sectors compare to each other, and this is incorporated in the selected values for the utility score. However, no information is found on how willing the sectors are to invest in relation to the network. Perhaps these values are collectively set too high or too low, and this could influence the system behaviour. The interaction regarding the assurance between the network and the consumers is based on characteristics of the 'who first' dilemma. In this thesis, this assurance is assessed by measuring the distance between the transitioned network and the specific node. It is questionable whether this assurance can be based on just distance, or that formal agreements between the involved parties also play an important role. However, this latter is considered outside the scope of this research. This limitation is most difficult to overcome, market research could help, but as the knowledge of the transition and hydrogen is currently limited, the answers of the market research might not be valid.

A third limitation relates to how the network is represented. As described in section 5.2.4 there is variation in the way the random network is formed, but this variation is only found in the randomness of the location of the nodes, and therefore in the links that are formed between them. It is a limitation that only this one type of network is subject to the different strategies and that no other type of topologies, such as scale-free networks, were examined. This would make it possible to test not only the effect of adaptation strategies but also the robustness of a particular topology.

In the current model, there are three country-based topologies available; however, adding additional networks in the same manner as the three countries now included, is very time-consuming.

As a consequence, it is a limitation that it is not possible to load in data of an existing network and test the strategies on real-life networks. This would improve the applicability of the model. Additionally, with more possibilities for the topology, this network transition model could also be applied to other fields, for instance, the transition to a fibre-optic network, or the implementation of new transportation options such as bullet trains in urban areas which are lacking space for two separate railway systems. Due to the fact

that this model focuses on the system level of network evolution, the principles can be applied to all kinds of focus fields, and therefore more options for topologies would have been an improvement.

The last limitation is the way the model is programmed. When the size of the network increases, the number of options to be considered for the network transition also increases exponentially. This leads to long run times. Consequently, the number of replications per experiment is limited, and the amount of experiments has also been kept to a minimum. This limitation could be addressed by looking where the code could be made more efficient or by leaving out options, such as the possibility to construct new pipelines. However, by leaving out important options, a part of the essence of the model would be lost.

9.2 REFLECTION ON THE VALIDITY OF THE MODEL

The traditional view on validation to check whether the model is an accurate representation of the system it represents (van Dam et al., 2013). To do so, comparisons are drawn between the results of experiments and real-world data. However, in the case of agent-based models, there are models where this type of validation is not possible. This is the case when there are no 'real' systems available to make a comparison to. This is the case for the model in this thesis which focuses on a network transition on a system level.

In section 8.4 a limited validation is performed. This validation focused on the purpose of this research and whether this purpose was accomplished with the model. There are other methods for validation. Four examples are described by van Dam et al. (2013). Suggestions are historical replay, face validation through expert consultation, literature validation and model replication.

Historic replay was unfortunately not an option to validate this model. This model cannot be compared to a real-world situation, as it describes the transition of a network on a system level.

Face validation through expert consultation could have been applied for validation, and this has been considered. However, here again, the fact that this model does not represent a real system makes it complicated. The level of abstraction and simplification could be distracting. Expert validation is a very subjective method and depending on the experts consulted, different outcomes can be received.

Validation by literature comparison is also considered a method for validation. As indicated in chapter 2.2, no research has been conducted in the field of network transition based on and competing with, and existing infrastructure. However, literature can be used to validate the results generated by the model. As explained the model itself cannot be validated, so the validating results is the best there is. This is partially done in the next section, where a reflection is made on the generalizability of the results

Validation through model replication is very time consuming, and therefore

this was not an option within the time frame of this master thesis project.

The effect of this limited validation is that the results in regard to the exact numbers and percentages are not validated and cannot be used as a prediction. Even when the correct topology had been applied in the model, the precise results could deviate from the real-life situation. However, the trends are validated, so the model is useful to bring to light the effect of the strategies in regard to the behaviour of the system, and this was the objective of this thesis.

9.3 REFLECTION ON THE GENERALIZABILITY OF THE RESULTS

In this section, the generalizability of the results of this thesis is discussed by reflecting on the results and indicating how the results can be interpreted and applied in real-life situations. First, the insights that are acquired in the experiments for the tactical options are discussed. Second, the results of the strategies will be reflected upon.

The effect of the variation in the starting topology

One of the main findings of the experiments is that the success of a tactic strongly depends on the starting topology of the network. As described in 5.2.4, the starting topologies that are varied within scenarios are different. However, the way the topologies are constructed and build-up are the same. In this thesis, the differences in topologies are based on the different location of the different types of nodes and with this, the links that are formed between the nodes. In this thesis, the starting topology is constructed by adding new nodes one by one and placing the nodes on a random location and then connecting the new node to the closest connection node in the network. More fundamental topological differences could be found if the network would be built up in a different way. This could either be a scale-free network, where the degree distribution of the nodes follows specific power laws, or more typical structures such as tree, star or ring topologies. However, since the 'minimal' variation of the location of the nodes in this research already indicated that the specific starting topology in a scenario determines the effectiveness and outcome of a tactic, it can be expected that a more fundamental change in topology creates larger differences within the results.

The outcome relating to the significance of a topology is also supported in the literature. Oikonomou and Cluzel (2006) indicated that the topology is from considerable importance as the topology determines the effect of the changes. Even though these changes are local, the network dynamic behaviour is affected. Therefore, the topology is a determining factor to the change or transition of a network (Oikonomou and Cluzel, 2006).

Consequently, it can be concluded a starting topology has an effect on the outcome and that this is generalisable for further use of the model. In the specific situation of the transition of the natural gas infrastructure to hydrogen, the main takeaway would be that it is important to look at the characteristics of the network and apply different strategies on this specific network. Best practices in other situations and other countries should not be copied without further considering the differences and the consequences of these differences on tactics and strategies.

In the Netherlands, with the double grid, this is even more pressing. The calculation in appendix K shows that the costs, based on the same input parameters as the model, would be lower than most scenarios in the model. The Dutch topology, with its double infrastructure, seems to be opportune.

Investing in new pipes to overcome lock-ins

Another finding of the experiments is that allowing the construction of new pipe trajectories helps the system to overcome lock-ins. The evidence is strong, and it indicates that giving the system the option to consider new pipes in the local optimising process, leads to better results, while still mainly building forth on the existing infrastructure. In the Netherlands, there is an extensive gas network that can be used for hydrogen transmission. This makes it appealing to only use the existing network without constructing new pipes. Instinctively this would save cost. However, the insight of this research points out that relying only on adapting the existing network does not lead to the best outcome and therefore, the option for constructing new pipes on some critical points should be considered. Even in the Netherlands, where a double grid is present, the option of constructing new pipelines to connect certain nodes should be taken into consideration.

The importance of investing at the start of the transition

The third result is that the largest portion of the available budget should be spent at the start of the transition. This is not an uncommon stance, as this makes it possible to longer benefit from early investments. Goldsmith (2013) indicates that infrastructure projects can be seen as "cash cows" once the costs of the investment were depreciated. Furthermore, already in 1989, Aschauer (1989) claimed that there are positive growth impacts from infrastructure investments.

However, whether this tactic can be applied in real-life situations is very dependent on the situation. Decisions regarding budgets are often complicated, as there are often external investors involved who have their own priorities. Besides these priorities, the determined budget, the ambition of the project and the technology can change over the course of 30 years. Even at this present time, there are different sources indicating different budgets. van der Walle (2020) talked about expenses between 1,3 and 3 billion euro for the transportation and storage of hydrogen, while the report of Gasunie (b) limited this to about 1,5 billion euro. It is difficult to set out a long-term tactic for an aspect that is likely to change over time.

In addition to the realisation of a hydrogen network, an important aspect to consider before investing in the network is the demand for hydrogen. The current hydrogen production cannot fulfil the full potential demand. It can be expected that the hydrogen production will increase over time, but this will not occur all at once. Significant investments in a hydrogen infrastructure, for which there is no demand yet, are therefore needless. Additionally, these early investments would actually hinder the energy supply, as a part of the infrastructure cannot be used by either natural gas or hydrogen. Subsequently, as indicated above, the situation can change. When spending the biggest portion of the budget at the start of the transition, a big part of the investment is locked in the new infrastructure, and the future option space is determined by these investments. This potentially limits the ability to react to changes in the future. Nonetheless, the results do indicate that the system benefits from early investments, so this insight can be generalised to invest maximally according to the available budget and maximal capacity of the system and the foreseen future.

The effect of an export corridor

The results of the experiments with the export corridor show that an export corridor does not affect the total expenses and the hydrogen delivery. These two KPI's do not reflect on the effect that is created by the implementation of this tactical option. However, the volume hydrogen that is exported is significantly higher with an export corridor. Therefore it can be said that this tactical option is useful in the goal it aspires. With political considerations in mind, it is wise to prioritise the flow of import and export.

The local optimization criteria

The last conclusion concerning the tactical options is that the local optimisation based solely on utility does not lead to the best outcomes for the whole system. For the Dutch situation, this can be translated to the advice not to focus on single big wins based on a high contribution for only a part of the system, but also consider both the costs and the contribution. This way, the risk of spending too much of the budget on a part of the system, and therefore not on the whole system, is minimised.

The strategies

The strategies that focus on the minimisation of costs have significantly lower expenses than the strategies that maximise the hydrogen delivery. A critical trade-off needs to be made in this case between costs and hydrogen delivery, taking into consideration that there is a strong lock-in effect in the strategy that focuses on low expenses.

It is reasonable that there is a relation between costs and hydrogen delivery. If a lock-in occurs, the development of the network stagnates and therefore no costs are made. The hydrogen delivery however will also remain low. This result is generalisable. This result can be translated to the insight that it is important first to establish certain boundaries between which there is

room to explore strategies.

The strategies that included the possibility of the export corridor delay the lock-in. This export corridor therefore has a positive effect on the volume hydrogen that is delivered, while the Dutch international position as a gas transit country is also maintained. This effect is logical, as the tactic of the export corridor also pointed out this effect. However, now applied in the strategy confirms that this tactic does not react with other tactics and results in the same outcome

The betweenness- and closeness centrality as predictors for the effect of tactical options and comprehensive strategies

The results of both the individual tactics and the comprehensive strategies indicate that there is no relation between the average betweenness centrality and average closeness centrality of a network.

An explanation for this lack of a relation can be found in the way that the centrality measures are calculated. In this model, the betweenness centrality is calculated as the number of times a node is on the shortest path between every two other nodes. The closeness centrality is calculated as the distance a node is located to every other node. In this model, the type of node is of high importance when differentiating between source nodes and sink nodes. This distinction is not included in the calculation of the centrality measures. The location of source nodes, in relation to the location of the sink nodes is of crucial, as the flow of hydrogen and natural gas occurs between source and sink nodes. The centrality measures of sink nodes to sink nodes, or source nodes to source nodes, are therefore not relevant but are included in the average that is calculated.

This information is not included in the current calculation of the centrality measures, and therefore these centrality measures of the network do not provide the information needed. In order to use the centrality measures as an indicator for the effectiveness of strategies, a differentiation should be made between a hydrogen centrality measure. This can be done by calculating the 'hydrogen centrality'; where the centrality is calculated between hydrogen source nodes and sink nodes that are open for the consumption of hydrogen, and by calculating the 'natural gas centrality'; where the centrality is calculated between natural gas source nodes and sink nodes that are open for the consumption of natural gas.

This thesis started as a curiosity-driven research to find out how a natural gas network transitions into a hydrogen network. Hydrogen is seen as a promising new, and most importantly, carbon-free, energy carrier that will play an essential role in the future energy system of the Netherlands. The existing natural gas infrastructure is deemed to be used for this new to be developed hydrogen infrastructure. However, there is still a demand for natural gas, and it is not possible to transport both gases through the same pipeline at the same moment.

It inspired to obtain knowledge on how such a new hydrogen network would transition and how different strategies could influence this transition. The goal of this research is to uncover the behaviour on a system level. An agent-based model, where rule-based behaviour could be implemented, is used to represent this network transition. Simulation based on different scenario's based of tactical choices gave insight in the behaviour of the network. Insights in the network development on a system-level provides more depth for deliberations and should be considered in the (optimisation) approach of a future hydrogen energy network.

In this chapter, the different sub-questions that were formulated in section 3.3 are answered, followed by answering the main research question. After this, both societal and scientific contribution are addressed. This chapter ends with some recommendations for future research.

10.1 ANSWERING THE RESEARCH SUB-QUESTIONS

In order to answer the main research question, four sub-questions were formulated in section 3.3. These questions will be answered below.

Sub-question 1: How should, based on graph-theoretical concepts, the natural gas and hydrogen infrastructure, including the transformation based on strategies, be represented?

Based on desk research, the natural gas network in this thesis is represented as a graph with nodes and edges. The nodes represent:

- source nodes; hydrogen source nodes or natural gas source nodes, or
- sink nodes; different sectors with a natural gas demand, a potential hydrogen demand, or
- export nodes.

The sectors that are included in this thesis are:

- the industrial customers,
- energy generators,
- the customers that are supplied with gas through the distribution grid, which are the built environment and the mobility sector.

The feature of the Dutch grid, where there is a separate infrastructure for high and low calorific gas is excluded in this model allowing the model to create more general insight, useable beyond the Netherlands.

The edges in the graph represent excising natural gas pipelines, new hydrogen pipelines and temporary tank trajectories.

Initially, the graph only consists of the excising natural gas pipelines, the so-called starting topology. However, the network continually has opportunities to evolve. This can be in the form of a new hydrogen or natural gas pipeline being constructed, a natural gas pipeline being changed to a hydrogen pipeline, or a temporary edge being activated as a tank connection.

The effect of four tactical choices on the network transition behaviour were tested. The tactics are the following:

- priority to base the local optimisation of a network transition on,
- including new pipes to be constructed in the excising graph,
- prioritising the export of both hydrogen and natural gas,
- allocate the available budget over time in different patterns.

Based on the effect of these tactics on the behaviour of the network, four comprehensive strategies are constructed. These strategies are then applied to a random network, similar as the network where the tactics were tested, and a network based on the low-calorific natural gas network in the Netherlands, the natural gas network of Belgium and the UK. These country-based gas networks are based on the structure of the transmission network, and the location of the sink nodes is random.

Sub-question 2: How should a conceptual model of the transition to a hydrogen infrastructure, based on an already established natural gas infrastructure, be made?

The answer to the first sub-question provides a system description that can be translated into a conceptual model.

The system is broken down into agents, objects and the environment. The agents are the different source and sink nodes, and the objects represent the different types of edges. The environment composes of the starting topology and the budget that is available per time step. The topology is determined by the location of every node, and the edges between these nodes.

How the different agents and the object interact with each other and the environment is visualized in figure 10.1.

The performance of the system is evaluated based on four KPI's.

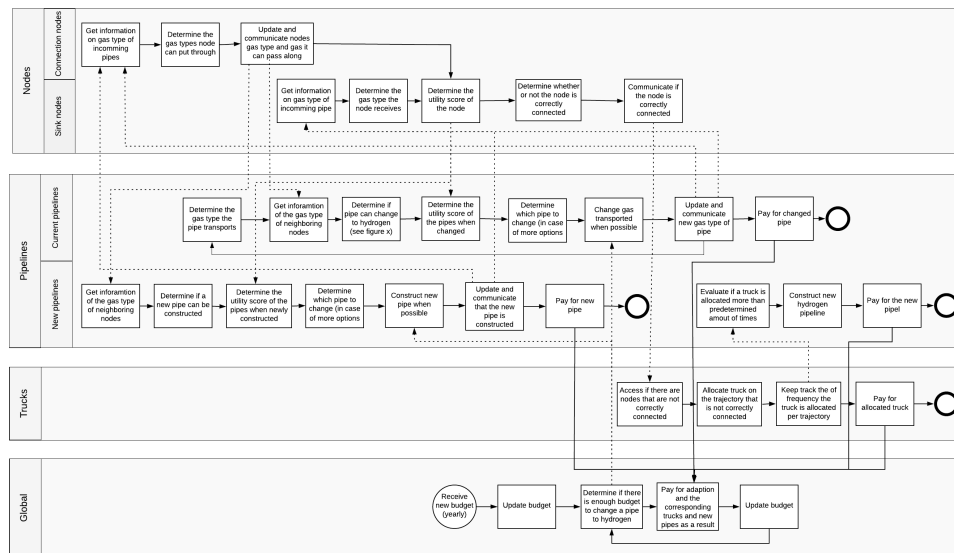


Figure 10.1: BPMN inspired diagram that captures the conceptualisation of the evolution of a hydrogen network

- the costs spend,
- the hydrogen delivery,
- the volume hydrogen that is exported,
- the extent to which the network has changed.

Sub-question 3: What is the effect of transition strategies for the transition path towards a hydrogen infrastructure?

The conceptual model of the second sub-question is translated into an agent-based model which is implemented in Netlogo. The developed agent-based model has numerous settings where the topology can be adjusted, the settings for gas demand can be altered, and the development of the utility scores can be adapted. Furthermore, the model interface allows the user to test any combination of tactics. In the experiments used to uncover the effect of transition tactics, a base case scenario was constructed that could serve as a basis to compare the output of the tactics.

The first tactic looked into the criterium to base the local optimisation on. The results indicate that the expenses are always lower when the option of constructing new pipes is not given, and the local optimisation is based on the lowest costs. In most scenarios, the delivery of hydrogen is also higher without the option of new pipes. Nevertheless, there is one scenario where the hydrogen delivery is maximal. This is in the situation where the local optimisation happens based on utility/cost, and the option for new pipes is included.

The second tactic is concerned with prioritising the export and import flow of both hydrogen and natural gas. The results indicate that this export corridor does not hinder the hydrogen transition and does not lead to

significantly more costs. The hydrogen corridor only makes a significant difference in the volume hydrogen that is exported.

The experiments with the third tactic indicate that the option to construct new pipes is essential to overcome lock-ins. The way to select new pipes to be constructed should be based on the local optimisation process and not be based on intensively used tank connections.

The fourth tactic indicates that it seems wise to spend the largest part of the budget at the start of the transition, as the system then can benefit the longest from these investments. This tactic lowers total expenses and improves hydrogen delivery and export.

Based on the results of the four tactics, four comprehensive strategies were formed. These either focus on the minimisation of costs, or the maximisation of hydrogen delivery and are constructed for both an available export corridor and no export corridor. The scenario that focuses on the minimisation of costs, locally optimises based on the lowest costs, and no new pipes are constructed. For the strategies that maximise the hydrogen delivery, the local optimisation is based on utility/cost and the option to construct new pipes is included in this local optimisation process. The strategies where expenses are minimised showed strong lock-in effects, and the outcomes strongly depended on the starting topology. The lower expenses are partially a result of this lock-in effect, where the transition of the network stagnates, and no new expenses are made. The inclusion of an export corridor postpones this lock-in effect. The inclusion of the corridor is therefore beneficial for the volume hydrogen delivered to the export node and the total volume hydrogen used in the network.

Sub-question 4: How can the insights on system-level be deduced and interpreted to benefit the transition to a hydrogen infrastructure?

By constructing strategies based on the results of the experiments with the tactics, it is possible to apply the strategies to country-based topologies. With this, a broader insight is created. Not only country-specific insights are created, but also the effect of a topology on the effectiveness of a strategy is underlined.

The experiments with the tactical options resulted in four main insights for the transition of the natural gas infrastructure to a hydrogen infrastructure. The first insight stresses the importance of the characteristics of a network and concludes that best practices in a particular infrastructure should not be copied to another infrastructure without any further consideration. For the infrastructure in the Netherlands, with the double grid, this even more pressing.

Second, the current natural gas network can be used for hydrogen, and this is beneficial. However, exclusively adapting the existing network does not lead to the best outcome, and subsequently, the option for constructing new pipes on critical points has to be considered.

Third, it is advised to invest maximally according to the availed budget, the maximal capacity of the system and the foreseen future.

The last insight is the advice not to focus on high contributions for small parts of the system at the expense of the budget. With this, there is a risk of spending too much of the budget on individual system components, with the effect that the optimal potential of the full network transition is not reached. The budget is a limiting factor, where to spend it should always be considered.

Within the constructed strategies, the strategies focusing on the minimisation of costs structurally have lower expenses. However, in the case of the random starting topology, this is always at the expense of the hydrogen delivery as these strategies cause lock-ins. The export corridor delays these lock-ins and is therefore not only beneficial for the hydrogen export, but also for the hydrogen delivery. When applying the strategies to country-based networks, it becomes evident that the topologies based on the Netherlands and the United Kingdom are not that susceptible to lock-ins. Therefore, in regard to hydrogen delivery, the strategy based on costs minimalisation and the strategy based on hydrogen delivery is not that different. This effect in the topology based on the Netherlands and the United Kingdom can however not be explained by the average betweenness centrality or by the average closeness centrality of the network. The reason why it can't be explained by these two metrics is that they are both calculated by taking the whole network into account, while to be insightful, they should have only been calculated for the potential paths the hydrogen would take.

The results show that the Dutch-based topology is not as susceptible for lock-ins as the random topology and the topology based on the Belgium network. This is despite the network in the model only being based on the low-calorific gas network. The fact that there is a double grid for hand will ease the technical part of the transition, as there is the possibility to provide both hydrogen and natural gas in many parts of the country. This means that the transition is less fundamental, and end customers can switch from a natural gas user into a hydrogen user gradually.

10.2 ANSWERING THE MAIN RESEARCH QUESTION

In this research, an agent-based model was created to get more insight into the transition of a hydrogen network based on a natural gas network. The goal was to answer the main research question, which is formulated as followed:

How do different transition strategies for the transition of a natural gas infrastructure to a (partial) hydrogen infrastructure perform over time?

To get a better understanding of the fundamental principles that drive this transition, this research has been executed on a system level to uncover the relevant factors. This research did not intend to calculate and optimise the transition of a specific hydrogen infrastructure. It aims to get insights

into the processes on a general level. This allows for more generalised insight which is not specific for a certain (part of an) infrastructure. With this system-level approach, it is possible to investigate different strategies based on the network characteristics and unravel the extent to which different strategies impact the evolution of the new infrastructure, and receive insights to how networks evolve based on an established infrastructure.

After studying the Dutch natural gas network, looking how gas infrastructures are set up in other countries and consulting the literature, an agent-based model was constructed that models the transition of a network based on an already established infrastructure. Four different tactics were tested in a total of six experiments. Based on the results of these experiments, four comprehensive strategies were constructed, which were applied on topologies based on the Netherlands, Belgium and the United Kingdom. These experiments lead to the following results.

- The topology of an infrastructure matters for the effect of strategies.
- The construction of new pipes is essential for overcoming lock-ins. Where and when these pipes are constructed, should be included in the local optimisation process.
- It is best to spend the largest portion of the total budget at the beginning of the transition period, as this way, the system benefits the longest from these investments.
- An export corridor does not lead to higher expenses while it can help to delay lock-ins.
- When optimising locally, the costs criterium should always be considered and included. The best local optimisation strategy is based on utility divided by costs.
- The overall average betweenness centrality and closeness centrality of a network are not good predictors for the effectiveness of a tactic or strategy.
- In the random topology and topology based on the Belgium network, there is a large risk for lock-ins. For this reason, in Belgium, the optimal strategy is to maximise the hydrogen delivery. This way, many lock-ins can be prevented, allowing the network transition to continue. In the topologies based on the network in the Netherlands and the United Kingdom, the risk for lock-ins is less present. A (partial) overlay between the strategy that focuses on minimisation of cost and maximisation of hydrogen delivery is found. In some cases, a trade-off between costs and hydrogen throughput needs to be made. However, in other cases, the situation prevails that the same hydrogen delivery is reached with both strategies. In this last case, the strategy based on minimalisation of cost leads to lower expenses with the same hydrogen delivery and is this is then the optimal strategy.

These results can be translated into six concrete insights that can be applied to real-life infrastructure planning based on an existing network.

- The first insight stresses the importance of the characteristics of a network and indicates that best practices in other infrastructures in other countries should not be copied without any further consideration.
- Second, purely adapting the existing network does not lead to the best outcome, and therefore the option to construct new pipes on some critical points should be considered. The construction of new pipes helps to overcome lock-ins and therefore has a positive effect on the system outcome.
- The third insight is that it is best to invest maximally according to the available budget, the maximal capacity of the system and the foreseen future. With this, the system can benefit the longest from the investments.
- The fourth insight is to be considerate about letting the network transition into certain geographic areas where the contribution is limited to only a small part of the network.
- The fifth insight is that it is wise to determine boundaries for the performance of the system to ensure that the system does not minimise costs at the expense of other KPI's.
- Specific to the topology based on the Netherlands and the United Kingdom, there are situations where the strategy that minimises costs reaches the same hydrogen delivery as the strategy that maximises the hydrogen delivery. This reinforces in fact in the first insight! The specific situation and location of nodes should be reviewed in order to determine the optimal strategy.

With a better understanding of how an infrastructure evolves, lessons can be drawn that can be applied to the development of the hydrogen infrastructure. These insights can improve this development in such a way that is beneficial to the energy transition.

10.3 RECOMMENDATIONS FOR THE DUTCH TRANSITION OF THE HYDROGEN INFRASTRUCTURE

In regard to the large challenge of the energy transition and the needed hydrogen infrastructure as a part of the energy transition, this research provides insight that can be beneficial for the transition of the natural gas infrastructure.

First of all, the Dutch infrastructure has the unique situation where a large part of the network comprises of a double system with both high-calorific pipelines and low-calorific pipelines. This is an opportunity to start the transition by transitioning one of the two systems. For instance, by keeping the high-calorific gas network intact while transitioning the low-calorific network to hydrogen. With this, it is possible always to supply the consumers of high-calorific gas. Whenever the hydrogen infrastructure has evolved far enough, the consumers have the choice between the two gasses and can

make the transition more gradually. For the heavy industry and electricity generators, such an investment is high, being able to do that in phases would make it more acceptable. Additionally, for the transition in general with this possibility to deliver both gasses, the risk of lock-ins is mitigated.

Second, it is important to prioritise the flow of export and import of hydrogen and natural gas. In the Netherlands, it is less of a challenge to realise this, due to the double network. However, this priority should still be given. The Dutch gas infrastructure will benefit from this corridor as a big part of the country will automatically be in closer proximity of both gases. Furthermore, it does not lead to higher investment costs and above all, the international position of the Netherlands is strengthened among with the additional benefits of the profits for the transit of gas.

Furthermore, the results of the four strategies applied to the topology based on the Netherlands indicate that there are situations where the same hydrogen volume is obtained with the strategy that focuses on the minimal cost compared to the strategy that focuses on maximal hydrogen throughput while saving costs. For this reason, it is recommended that a more specific analysis is carried out with the precise location of all sources and sinks to determine the favourable strategy and based on these results make a deliberate trade-off between costs and hydrogen throughput.

In line with the previous recommendation, it is plausible that only a limited number of new pipes need to be constructed in the Dutch network for the system to thrive. It is wise to include the possibility of new pipes in the decision-making process.

The last recommendation is to closely observe how the supply and demand of hydrogen and natural gas evolve and invest confirming this development. Ensure that the supply is met by ensuring that the demand side can be reached by establishing a hydrogen infrastructure.

10.4 SCIENTIFIC CONTRIBUTION

Previous research has pointed out that the use of an existing infrastructure speeds up the transition to new energy sources like hydrogen (Baufumé et al., 2013). The possibility of using the natural gas network for the distribution of hydrogen has been confirmed, and various studies looked into the technical aspects regarding the physical change of the infrastructure (Messaoudani et al., 2016; van der Zwaan et al., 2011). Many studies focused on finding the optimal hydrogen network by applying optimisation techniques such as mixed-integer linear programming (Mukherjee et al., 2015; Baufumé et al., 2013; Hugo et al., 2005; Kim and Moon, 2008; Kamarudin et al., 2009). However, these optimisation techniques do not take into account the transitional process of network development, which is characterised by path-dependency, lock-ins, network effects and shared effort (Chappin and Dijkema, 2008; Davis et al., 2010; Nikolic et al., 2008; Xie and Levinson, 2009). The conducted literature search shows that a lot of research has focused on

the evolution of infrastructures in the mobility sector, but the transition of energy infrastructures is relatively unexplored. Studies that have been performed in the energy domain, mainly focus on the design of these complex infrastructures and how to assess them. The transition from one infrastructure to another remains uncharted.

In consideration to the already conducted research, this thesis specifically looked into how a natural gas network transitions from fulfilling one purpose, the distributing of natural gas, to another, distributing of hydrogen while taking path dependency into account. The focus of this research was to study the effect of tactics and strategies on this transition and how these strategies would change the behaviour of the system regarding the transition from natural gas to hydrogen of the network. The effect of the tactics and strategies were not only reflected upon by the KPI's alone but were considered in regard to the average betweenness centrality and closeness centrality of the nodes in the network.

This approach is different from previous studies as it considered network properties such as path dependency while evaluating the roll-out of a hydrogen network. In order to do so, simplifications were made, and assumptions were drawn. With this, the system used was not a direct representation of any real-life situation. However, this research had the ambition to give system-level insight into how a network transitions and this ambition was met. A common approach for network planning is the optimisation of the system as a whole, where numerous settings are tried, and the optimum is determined. This black box optimisation process does not take into account the step for step approach that is needed for this transition, and without taking this into consideration, there still would be no insight on how to manage the transition optimally taken into account the properties of a network. Even with many assumption and simplification in regard to the current Dutch natural gas and hydrogen system, system behaviour is uncovered, and the effect of specific strategies is determined. Linking network centrality measures to the results is also novel in this field of the transition of a hydrogen network.

In this research, a start is made to understand how networks evolve on a step for step bases when a particular infrastructure is available. This has led to the insight that the topology of a network is of high importance for the effect of a strategy. However, the average betweenness and closeness centrality of the nodes in the network are not indicators for the effect of these strategies. This could be different if those indicators would be calculated in a different way, as discussed earlier in section ???. The second insight is that when basing the transition of a network on an existing network, it is important still to consider the construction of new edges for this transition. A third insight is that the system benefits from investments at the start of the transition period. A negative aspect here is that high investments also means a commitment to continue. The fourth insight is to not just look where the utility is potentially the highest but to keep an eye on the big picture and make sure that there is a strong basic infrastructure. After that, a more regional approach can be adapted. The fifth insight is to establish boundaries

in regard to the minimal performance of the system.

The insights acquired in this specific field of a hydrogen and natural gas infrastructure can, with some changes, also be applied to other research fields such as the evolution of a fibre-optic network, or the implementation of new transportation method such as bullet trains in urban areas where there is no room for two railway systems. As this concept on network transition in combination to an existing network is not yet explored in the literature, this thesis provides the first building blocks, with the insights acquired and a first network transition model, from where further research can continue.

10.5 SOCIETAL CONTRIBUTION

Despite the many simplifications and assumptions, the system and the interactions within the system have led to better insights on system level. These insights on system-level still hold within the context they are placed. As the development of the hydrogen network will take over 30 years, it is possible that the infrastructural planning changes. The budget that is presumed to be available could be entirely changed under a new administration, a sudden innovation could make the production of green hydrogen cheaper, and with this, increases both the supply and demand. Another energy carrier can be found to be more feasible than hydrogen. A scan on innovative development makes this unlikely for the moment, but 30 years is a long time. With these uncertainties and the long horizon for infrastructural development, this research has therefore provided a handle to formulate a more nuanced approach than overall system optimisation. This nuanced approach gives a better insight into the network transition and the influence of specific strategies. This creates a more resilient process of the development of a hydrogen infrastructure, and could save costs for society.

10.6 RECOMMENDATIONS FOR FUTURE RESEARCH

The first recommendation is to expand the current model by including one or more suggestion. The first suggestion builds forth on one of the limitations that was addressed in section 9.1. This is to make this model more generic and applicable to all kinds of networks by including more default topologies in the interface. Also, including an extension that makes it possible to load in the data of a specific network, would make this model even more applicable.

A second recommendation is to calculate the utility of a pipe by looking at the added contribution for the system as a whole, as more elaborately explained in 9.1. This would increase the likeliness of the model.

Third, the model could include the possibility to optimise more than just one step ahead with an adjustable number of years. This option would also make the model more realistic. However, it will still be insufficient to allow an accurate prediction for the full time span of 30 years. This is just too long away with too many uncertainties, in our environment and in science

(innovation).

Furthermore, the centrality measures should be recalculated in such a way that the flow of hydrogen and natural gas is considered.

An additional recommendation is to increase the validity of this research. As indicated in 9.2, a validation method that was not applied in this research due to the labour intensity is validation by model replication. Implementing the network transition model in, for instance, MatLab could increase the insight into the network evolution based on an existing network. In MatLab it is also possible to optimise the entry system at one for the entire time span. This creates more possibilities to compare the different strategies.

Last, this research can be applied to other infrastructures. With this a more general understanding of which aspects of the network evolution are linked to certain infrastructures, and which aspects generally hold true for overall network transition, is created.

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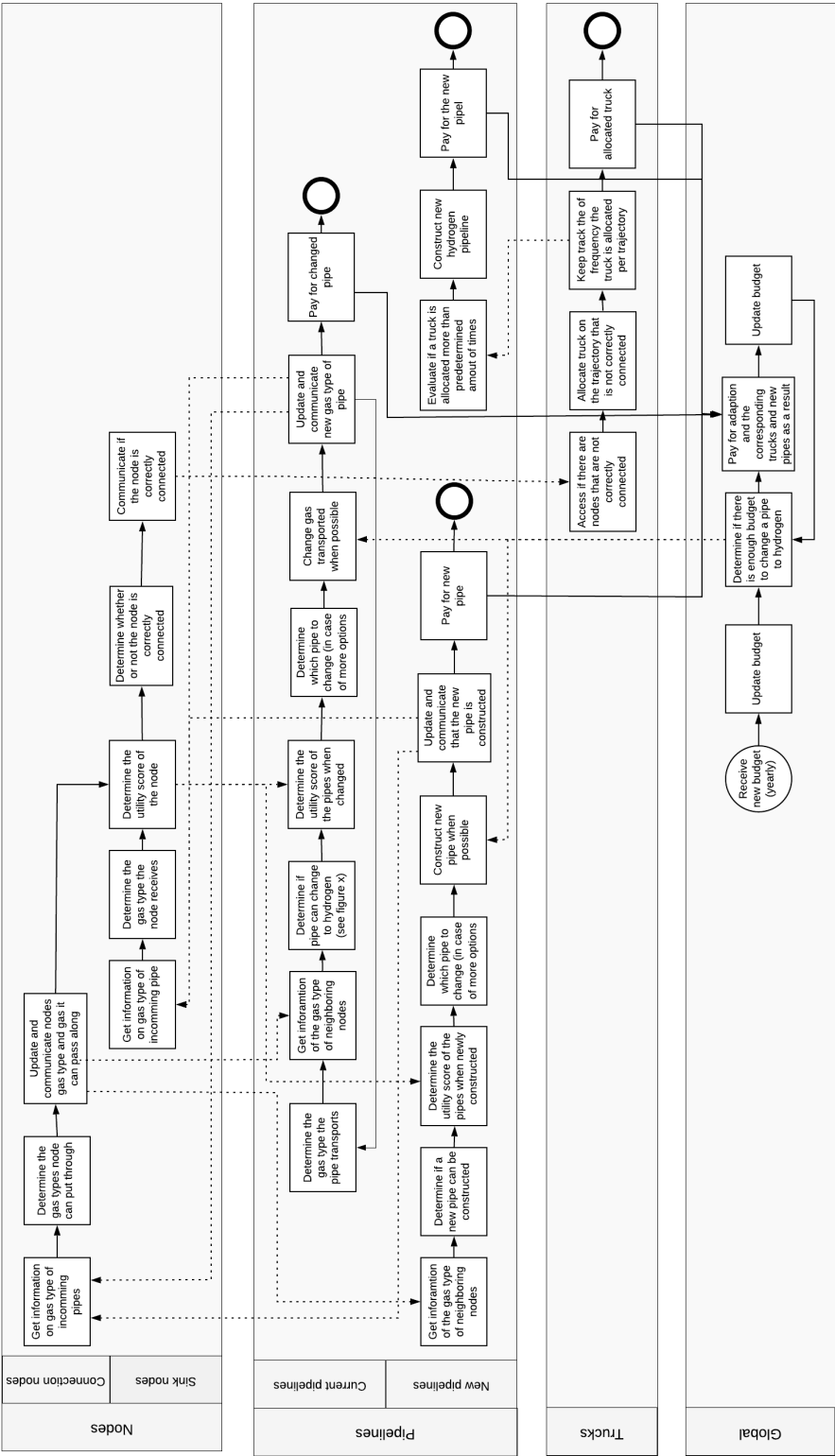


Figure A.1: BPMN inspired diagram

B

MODEL PARAMETERISATION

Category	Description	Type of value	Allocated value research
For the topology	Number of connection nodes	Absoluut number	80
	Number of natural gas source nodes	Absoluut number	13
	Number of hydrogen source nodes	Absoluut number	4
	Number of industry sink nodes	Absoluut number	33
	Number of electricity generator sink nodes	Absoluut number	18
	Number of distribution nodes	Absoluut number	55
	Number of natural gas import nodes	Absoluut number	1
	Number of hydrogen import nodes	Absoluut number	1
	Number of natural gas export nodes	Absoluut number	1
	Number of hydrogen export nodes	Absoluut number	1
	Ring structure or connected network	Boolean	off
Gas demand	Combined demand natruaal gas in industries	Absoluut number	10
	Combined demand natruaal gas in the electricity generating sector	Absoluut number	13
	Combined demand natruaal gas in the distribution network	Absoluut number	11,5
	Combined demand natruaal gas for export	Absoluut number	54
	Combined demand hydrogen in industries	Absoluut number	24
	Combined demand hydrogen in the electricity generating sector	Absoluut number	11
	Combined demand hydrogen in the distribution network	Absoluut number	20
	Combined demand hydrogen for export	Absoluut number	22
For the utility score	Difference between different nodes of same sector	Fraction	0,1
	Starting value industry	Number	8
	Starting value electricity sector	Number	7
	Starting value distribution grid	Number	9
	Increase starting value per year for the industry	Number	0,15
	Increase starting value per year for the electricity sector	Number	0,1
	Increase starting value per year for the distribution grid	Number	0,1
	Start of this increase for the industry	Number	5
Price settings	Start of this increase for the electricity sector	Number	3
	Start of this increase for the distribution grid	Number	0
	Price for changed pipe	Number	200000
Settings for boundaries of utility	Price for new pipe	Number	2000000
	Price for truck	Number	19000
	Below which value no hydrogen is desired	Number	15
Settings to simplify the model	Above this value only hydrogen is desired	Number	19
	Below this value, this pipe will not be changed	Number	5
	Allow for more than one action per tick when there is enough money	boolean	on
	Allocate trucks when a node does not receive the correct gas type	Boolean	on

Table B.1: Parameters and chosen value for the model

The chosen values for the model are displayed in table B.1. With regard to the number of nodes for the topology, the intentions was to base it on the situation in the Netherlands. However, in some cases, the number of sinks was extremely large, and the Netlogo model could not place all sinks on a free spot. For this reason, the amount of some nodes, when the number was extremely large, was divided by ten or twenty. In all other cases, the number of nodes was divided by 2 keep the proportions somewhat correct. For starters, the amount of ch₄ entry points in the Netherlands is set on 13. This number is based on figure 4.2 where 27 entry points of natural gas are counted, and the number is divided by 2 for the proportions. The amount of h₂ source points is 7 as there currently are 4 grey hydrogen production sites in the Netherlands and there are plans for 3 green hydrogen sites (Leguijt et al., 2018). Similar to the ch₄ source nodes, this number is also divided by 2.

In case of the industrial nodes that are active in the Netherlands and have a connection to the grid, 330 points were counted in figure 4.2. This number is divided by 10 and with this, 33 industrial sink nodes are included in the model.

The amount of electricity generators is set on 18 in the model, as there are

36 gas fired power plants in the Netherlands (Entsoe).

In the Netherlands, there are 1100 points where the gas is branched out to the distribution grid (Gasunie, a). This number is divided by 20 to 55.

The demand of the nodes per sector combined are shown in table 4.1

For the import and export of both hydrogen and natural gas, the modelling choice was made to include 1 node for each. The reason for this is that the shortest path between and export and import was defined, and then labelled as the optimal route. In the strategy of the export corridor, these pipes are assured to deliver the hydrogen or natural gas. For modelling purposes, it was not possible to include more points. The demand for the hydrogen export was not described in literature or reports. For this, an assumption was made. The assumption is based that 40% of the natural gas consumption, is imported. When this is done for the hydrogen consumption of 55 billion m³, 22 billion m³ gas for export is chosen.

In regard to the starting values, the increasing starting values and the starting year of the starting value, the assumption with the following train of thoughts is made; The consumers via the distribution grid (built environment and mobility) are already either starting to move away from natural gas or have only a small consumption of natural gas. Besides that, there are already a lot of alternatives proven. This is the reason why the starting value is the highest of the three sectors, and also starts at the beginning of the model. However, the increase is relatively low as the effect of switching households and mobility to an alternative, is relatively small.

When considering the industrial clusters, for example, the gain is very big, but so far there is only talk of applying hydrogen in this sector, but concrete steps are not yet spoken for. The electricity generators are somewhat in between; there are concrete plans for one of the plants but for the others not yet. Also, gas is seen as a good option to keep in the energy mix while this does not have as big a carbon footprint as coal plants, but it can always be fired on to create a load when the RES generation is low.

When considering the price, it was found that the price per meter is € 2005 (Tzimas et al., 2007). The price of the adaption of the grid is set on 10% of the price of a new pipe, as indicated by van Wijk and Hellinga (2018).

The settings for utility are chosen by looking at the model behaviour. This should not be too high or too low that trucks need to be allocated every time, but extreme, but still likely, situations should be able to occur.

C | ASSUMPTIONS

Assumption	Topic	Content
1	Scope	The possibility of injecting hydrogen into the natural gas grid and creating a mixture is not considered
2		The technical aspects of the network change are not considered
3		The focus will only be on the infrastructure that needs to change, not on other aspects such as end-user application
4		The model will not look further than 2030
5	System representation	The different gas types of L-gas and H-gas are not taken into account, all natural gas is considered the same
6		Within the hydrogen generation nodes, no difference is made between the generation methods
7		Compressor, mixing and pressure stations are not included in the model
8		Connection nodes only have the function of structuring the network and no other purpose
9		No new nodes will be added during the runtime of the model
10		No nodes will be removed during the runtime of the model
11		Pipelines are not bounded by capacity
12		Pipelines do not have a direction in which they flow
13		Representation is not based on a specific existing network
14		The network will not be laid out double
15		The distribution network is not included as a network, only as a node
16		The total length of the distribution grid is included in the distribution sink node
17		Source nodes also represent import points
18		The cost of a pipe only consists of one time cost, no maintenance or other variable cost are included
19		Distribution nodes represent built environment and mobility sector
20		One time step is one year
21	Model assumption	The volume of gas over time is constant
22		The cost of options is fixed over time
23		There is enough supply to meet demand and demand is leading
24		There will always be export of both hydrogen and natural gas
25		The hydrogen consumption replaces natural gas demand completely
26		The capacity of the network is sufficient and not included
27		The utility score consists of two independent values, one bound to the sector, and the other bound to the state of the network

Table C.1: Assumption throughout the research

D | MODEL VERIFICATION

D.1 CODE WALK THROUGH

Every step and code is checked, whether it does what it intends to do. Different aspects of the code are studied. The order that procedures are called on is walked through. During some procedures, it is asked to print and show information in the command centre. While running the model, it can then be checked if the model does what it should do. An example of this is shown in figure D.1

```
to changing-network
[false budget < 0
[
  print " i am out of money so i go to the next tick "
  stop
]
[ while [ budget > 0 and there-are-pipes-to-change = true ]
[ make-pipe-switch
  show budget ; only last iteration before tick should be negative, as it continues until it has no money at the start of the tick
  show there-are-pipes-to-change ; should give true, if false it is not listening
  print " i made it past the loop to the next step "
]]
end
```

```
observer: 1.4871938174153894E7
observer: true
i made it past the loop to the next step
observer: 6054639.173918079
observer: true
i made it past the loop to the next step
observer: 3269197.6395331644
observer: true
i made it past the loop to the next step
observer: -7949887.888785123
observer: true
i made it past the loop to the next step
i am now out of money so i will go to the next tick
observer:
```

Figure D.1: verification by adding commands to be shown in the command centre

D.2 RECORDING AND TRACKING AGENT BEHAVIOUR

To test if the pipes and nodes behave as the should, the visual feedback on the interface is used extensively. The choice has been made to distinguish the characteristic of gas type by different colours; orange for natural gas, blue for hydrogen and yellow for both. By tracking an agent through ticks, it can be monitored if the agents' characteristics change as they should. An example of this can be found in figure D.2 where a distribution sink node is tracked. While the node has node-gas-type-h2 = false, it is connected to natural gas, and it is coloured orange. In the fourth image, it is connected to hydrogen, and now it is coloured blue. The other thing that can be seen is that the distance to hydrogen (distance-h2) decreases between the first and the second tick, but stays the same for one tick when this distance does not get smaller. The utility score is built up of a general starting value, that increases with 0.1 after the first tick (this is a setting that is chosen in the model settings in the interface), and the distance to hydrogen. It becomes apparent that the utility score increases every tick, but the increase is the biggest when the distance to hydrogen is reduced. When the node is connected to hydrogen, it does not have a need to be attached once more, so the utility is set to 1.

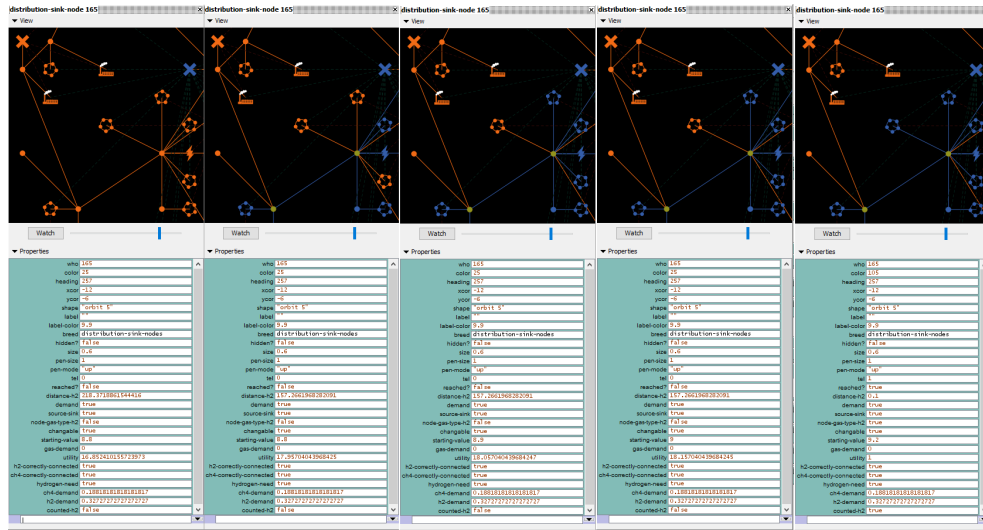


Figure D.2: Inspection of one agent

D.3 INTERACTION TESTING LIMITED TO MINIMAL MODEL

In this step, the model is tested when the model is run for just a few agents. Here it should be noticed that the model was constructed while only using a few agents. This made it easier to keep track of the different agents on paper and make small calculations. Excel was often used, and the network with the values for the different edges was frequently drawn on paper where first it was calculated which adaption would take place, and then by running the model one step, it was checked whether the expected behaviour also occurred. Once every while, the model was scaled up to more realistic settings to see whether the same behaviour as in the minimal model would still occur.

D.4 MULTI-AGENT TESTING

In this step, the model is scaled up to its intended size, and with the help of inspecting single agents here, monitors and plot indicate if the model behaves how it should. Different model runs are executed to ensure that the behaviour is not linked to a single setting.

E | CONSTRUCTION OF THE COUNTRY BASED TOPOLOGIES

The topology based on the countries is constructed by looking at the transmission network and localising these coordinates. These are then applied in NetLogo and the correct connections between the nodes are drawn. The area of the country border is defined and this is the location where the source and sink nodes were able to place themselves. This locating of the source and sink nodes is done randomly. The number of source and sink nodes is already brought down in comparison to the real situation, as otherwise, it was not possible to find a free patch for every node. For this reason, the exact location is of less importance, as not all nodes are included. In the situation of the Dutch based topology, the hydrogen source nodes and natural gas source nodes are placed at locations where the gas is fed into the system. In figure E.1, figure E.2 and figure E.3, the resemblance between the transmission network and the topology in the model can be seen.

The three topologies are significantly different from each other in regard to average betweenness centrality and closeness centrality, as can be seen in table E.1 and in table E.2.



Figure E.1: The way the Dutch based topology is formed



Figure E.2: The way the Belgium based topology is formed

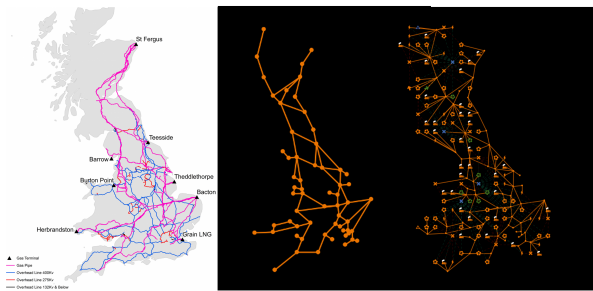


Figure E.3: The way the United Kingdom based topology is formed

	Random		Netherlands		Belgium		UK	
	tstat	pvalue	tstat	pvalue	tstat	pvalue	tstat	pvalue
Random			-51,40	0,00	-33,82	0,00	11,68	0,00
Netherlands					42,33	0,00	109,02	0,00
Belgium							60,26	0,00
UK								

Table E.1: Significance of the difference between the topologies in regard to average betweenness centrality of the network

	Random		Netherlands		Belgium		UK	
	tstat	pvalue	tstat	pvalue	tstat	pvalue	tstat	pvalue
Random			29,51	0,00	30,35	0,00	2,50	0,01
Netherlands					6,35	0,00	-171,86	0,00
Belgium							-166,29	0,00
UK								

Table E.2: Significance of the difference between the topologies in regard to average closeness centrality of the network

Some extra graphs are presented here. From this it can be concluded that there is no relation between the cost and the extent the network has changed, or a relation between the cost and the amount of hydrogen that is delivered. There is a relation between the amount of hydrogen delivered and the extent the network has changed. The results will therefore be very dependent on the topology of the network in the base case settings.

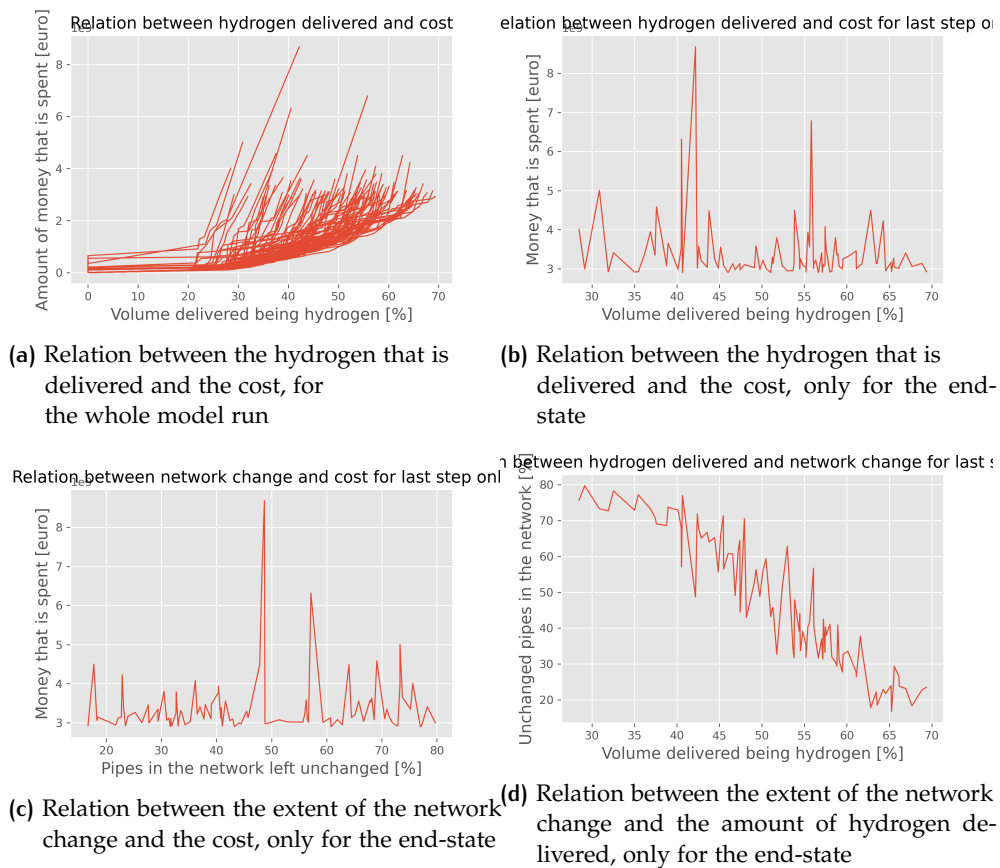
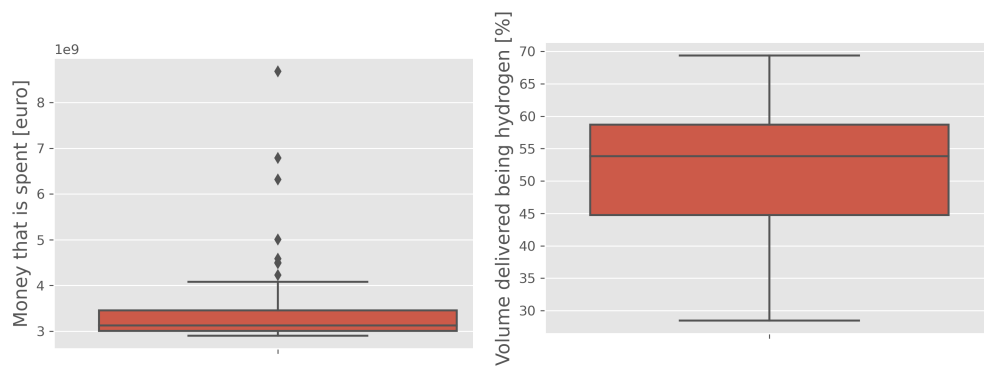
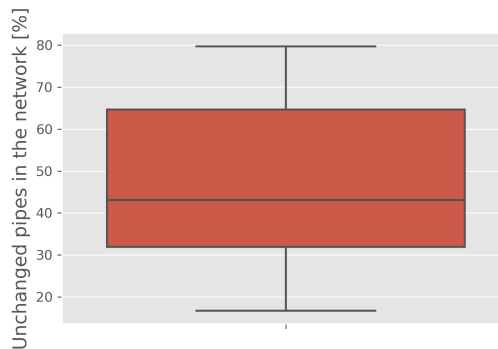


Figure F.1: Variability testing of the base case

The boxplots in F.2 show how the biggest variability can be found in the hydrogen delivery and the network change, while the variability in regard to the total costs stays limited



- (a) The total expenses at the last step of the model run for the 100 replication in the base case scenario
- (b) The percentage of the hydrogen potential that is delivered to customers in the last step of the model run for the 100 replication in the base case scenario



- (c) The percentage of the pipes in the network left unchanged in the last step of the model run for the 100 replication in the base case scenario

Figure F.2: Variability testing of the KPI's in the base case scenario in the last step of the model run

G

SETTINGS FOR ALL RAN SCENARIOS

In table G the tactical settings per scenario are shown.

Experiment	Scenario	Option for new pipe	Priority change	Time between strategies	Corridor	New pipe on truck connection	Time to construct a pipe	Budget allocation
1a	1	True	low cost	-	True	True	3	Equal
1a	2	True	high utility mean	-	True	True	3	Equal
1a	3	True	high utility max	-	True	True	3	Equal
1a	4	True	high utility/cost	-	True	True	3	Equal
1a	5	True	changing	-	True	True	3	Equal
1a	6	false	low cost	-	True	True	3	Equal
1a	7	false	high utility mean	-	True	True	3	Equal
1a	8	false	high utility max	-	True	True	3	Equal
1a	9	false	high utility/cost	-	True	True	3	Equal
1a	10	false	changing	-	True	True	3	Equal
1b	11	True	changing	Al three	True	True	3	Equal
1b	12	True	changing	Skip cost	True	True	3	Equal
1b	13	True	changing	Skip utility	True	True	3	Equal
1b	14	True	changing	Skip utility cost	True	True	3	Equal
2	15	True	high utility/cost	-	True	True	3	Equal
2	16	True	high utility/cost	-	False	True	3	Equal
3a	17	True	high utility/cost	-	True	True	3	Equal
3a	18	True	high utility/cost	-	True	False	-	Equal
3a	19	False	high utility/cost	-	True	True	3	Equal
3a	20	false	high utility/cost	-	True	False	-	Equal
3b	21	True	high utility/cost	-	True	True	1	Equal
3b	22	True	high utility/cost	-	True	True	3	Equal
3b	23	True	high utility/cost	-	True	True	5	Equal
3b	24	True	high utility/cost	-	True	True	7	Equal
3b	25	True	high utility/cost	-	True	True	9	Equal
3b	26	True	high utility/cost	-	True	True	11	Equal
3b	27	True	high utility/cost	-	True	True	13	Equal
3b	28	True	high utility/cost	-	True	True	15	Equal
3b	29	True	high utility/cost	-	True	True	17	Equal
3b	30	True	high utility/cost	-	True	True	19	Equal
3b	31	True	high utility/cost	-	True	True	21	Equal
3b	32	True	high utility/cost	-	True	True	23	Equal
3b	33	True	high utility/cost	-	True	True	25	Equal
3b	34	True	high utility/cost	-	True	True	27	Equal
3b	35	True	high utility/cost	-	True	True	29	Equal
4	36	True	high utility/cost	-	True	True	3	Equal
4	37	True	high utility/cost	-	True	True	3	Increasing
4	38	True	high utility/cost	-	True	True	3	Decreasing
Lowest cost	39	False	Changing	Skip cost	True	False	-	Decreasing
Maximal H2 delivery	40	True	high utility/cost	-	True	False	-	Decreasing

Table G.1: Tactical settings for the scenarios



EXTRA RESULTS TACTICAL OPTIONS

In this appendix, extra results of the experiments with the tactical options are given.

H.1 EXTRA RESULTS TACTIC OPTION 1

Ten different scenarios are created in experiment 1a. Tables H.1, H.2 and H.3 indicate whether the difference between the scenarios is significant for the KPI costs, hydrogen delivery and hydrogen export. The threshold of $p = 0,05$ is used to determine the significance.

From these three tables, it can be deduced that the difference for the expenses in the different scenarios are (with one exception) not significant. For the hydrogen delivery, the scenario where pipes are constructed, and the optimisation is based on utility/cost, is significantly better than most other scenarios.

Almost non of the scenarios is significantly better for the hydrogen export.

	true cost		true max utility		true ave utility		true utility/cost		true changing		false cost		false max utility		false ave utility		false utility/cost		false changing	
	tstat	pvalue	tstat	pvalue	tstat	pvalue	tstat	pvalue	tstat	pvalue	tstat	pvalue	tstat	pvalue	tstat	pvalue	tstat	pvalue	tstat	pvalue
true cost			0,44	0,66																
true max utility					1,36	0,18	0,67	0,50	0,85	0,34	0,05	0,96	-0,69	0,50	-0,47	0,64	0,52	0,60	0,31	0,76
true average utility							0,93	0,35					-1,25	0,21	-1,06	0,29	0,04	0,96	-0,20	0,83
true utility/cost									-0,47	0,64	-0,48	0,63	-1,61	0,11	-2,56	0,01	-1,04	0,30	-1,45	0,15
true changing									0,07	0,94			-1,42	0,16	-1,25	0,22	-0,27	0,79	-0,51	0,61
false cost											-0,94	0,35			-1,76	0,08	-1,61	0,11	-0,42	0,67
false max utility													-0,87	0,34			0,56	0,58	0,31	0,76
false average utility															0,31	0,76				
false utility/cost																	1,26	0,21	1,03	0,30
false changing																			-0,23	0,77

Table H.1: Significance of the difference between the scenarios in experiment 1a in regard to the costs

	true cost		true max utility		true average utility		true utility/cost		true changing		false cost		false max utility		false average utility		false utility/cost		false changing	
	tstat	pvalue	tstat	pvalue	tstat	pvalue	tstat	pvalue	tstat	pvalue	tstat	pvalue	tstat	pvalue	tstat	pvalue	tstat	pvalue	tstat	pvalue
true cost			-0,67	0,50			-2,74	0,01			-0,80	0,42	-0,45	0,66	8,61	1,21	-3,97	0,00	-0,80	0,43
true max utility					0,14	0,89			-0,16	0,87	0,39	0,84	10,54	7,99	16,28	1,27	-3,55	0,00	-0,16	0,87
true average utility							-1,94	0,05			-0,27	0,78	7,65	1,38	11,61	3,89	-3,10	0,00	-0,26	0,79
true utility/cost									1,97	0,05			13,55	3,47	19,54	1,43	-1,53	0,13	1,98	0,05
true changing											0,33	0,74			10,11	6,71	-3,28	0,00	0,01	1,00
false cost													9,07	1,22	13,96	4,76	3,49	0,00	-0,33	0,75
false max utility															9,60	9,06	-13,64	2,24	-10,18	5,00
false average utility																	-18,70	4,25	-15,53	3,58
false utility/cost																			3,30	0,00
false changing																				

Table H.2: Significance of the difference between the scenarios in experiment 1a in regard to the hydrogen delivery

Four different scenarios are created in experiment 1b. Tables H.4, H.5 and H.6 indicate whether the difference between the scenarios is significant for the KPI costs, hydrogen delivery and hydrogen export. The threshold of $p = 0,05$ is used to determine the significance.

From these three tables, it can be deduced that the difference for the expenses in the different scenarios is not significant.

For the hydrogen delivery, the scenario where the costs are skipped in the local optimisation process is better than the scenario where all three criteria

	true cost		true max utility		true average utility		true utility/cost		true changing		false cost		false max utility		false average utility		false utility/cost		false changing	
	tstat	pvalue	tstat	pvalue	tstat	pvalue	tstat	pvalue	tstat	pvalue	tstat	pvalue	tstat	pvalue	tstat	pvalue	tstat	pvalue	tstat	pvalue
true cost																				
true max utility			0,44	0,65																
true average utility					1,36	0,18	0,67	0,50	0,85	0,39	0,05	0,96	-0,69	0,49	-0,47	0,64	0,52	0,60	0,31	0,76
true utility/cost					0,93	0,35	0,29	0,77	0,42	0,67	-0,46	0,65	-1,25	0,21	-1,06	0,29	0,04	0,96	-0,21	0,83
true changing							-0,47	0,64	-0,48	0,63	-1,61	0,11	-2,56	0,01	-2,49	0,01	-1,04	0,30	-1,45	0,15
false cost							0,07	0,94	-0,71	0,48	-0,71	0,48	-1,42	0,16	-1,24	0,25	-0,27	0,78	-0,51	0,61
false max utility									-0,94	0,35			-1,76	0,08	-1,61	0,11	-0,42	0,67	-0,71	0,48
false average utility													-0,87	0,38			0,56	0,56	0,31	0,76
false utility/cost															0,31	0,76	1,45	0,15	1,25	0,22
false changing																	1,26	0,21	1,03	0,30
																			-0,29	0,77

Table H.3: Significance of the difference between the scenarios in experiment 1a in regard to the hydrogen export

are used, and where utility is skipped. is significantly better than most other scenarios.

	all tree		skip cost		skip utility		skip utility/cost	
	tstat	pvalue	tstat	pvalue	tstat	pvalue	tstat	pvalue
all tree			-0,15	0,87	-0,89	0,38	-0,32	0,74
skip cost					-0,76	0,45	-0,17	0,86
skip utility							0,63	0,53
skip utility/cost								

Table H.4: Significance of the difference between the scenarios in experiment 1b in regard to the costs

	all tree		skip cost		skip utility		skip utility/cost	
	tstat	pvalue	tstat	pvalue	tstat	pvalue	tstat	pvalue
all tree			-2,78	0,01	0,00	1,00	1,41	0,16
skip cost					2,68	0,01	4,30	1,67
skip utility							1,35	0,18
skip utility/cost								

Table H.5: Significance of the difference between the scenarios in experiment 1b in regard to the hydrogen throughput

In the plots in figure H.1, figure H.2 and figure H.3, the development of the KPI's over time is given.

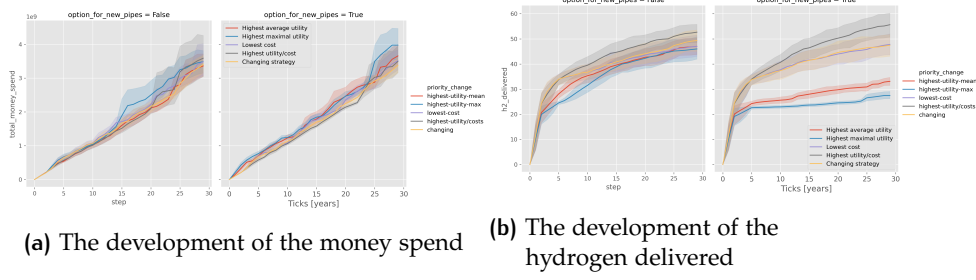


Figure H.1: Development over time for experiment 1A

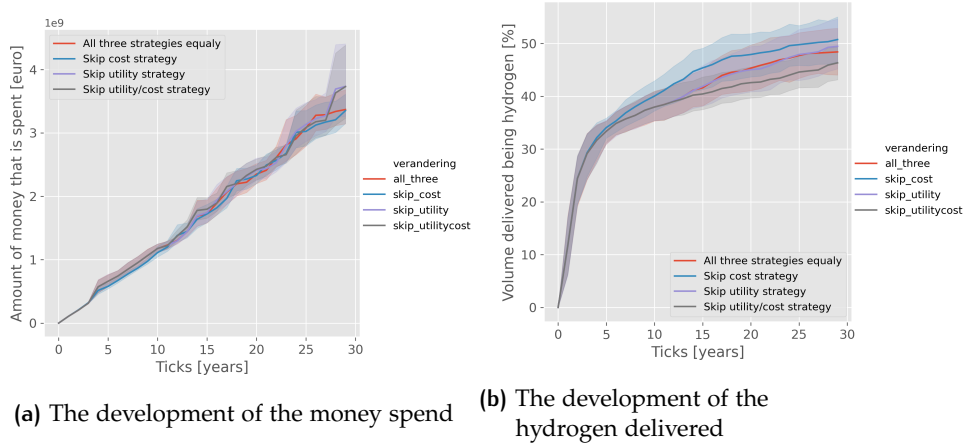


Figure H.2: Development over time for experiment 1B

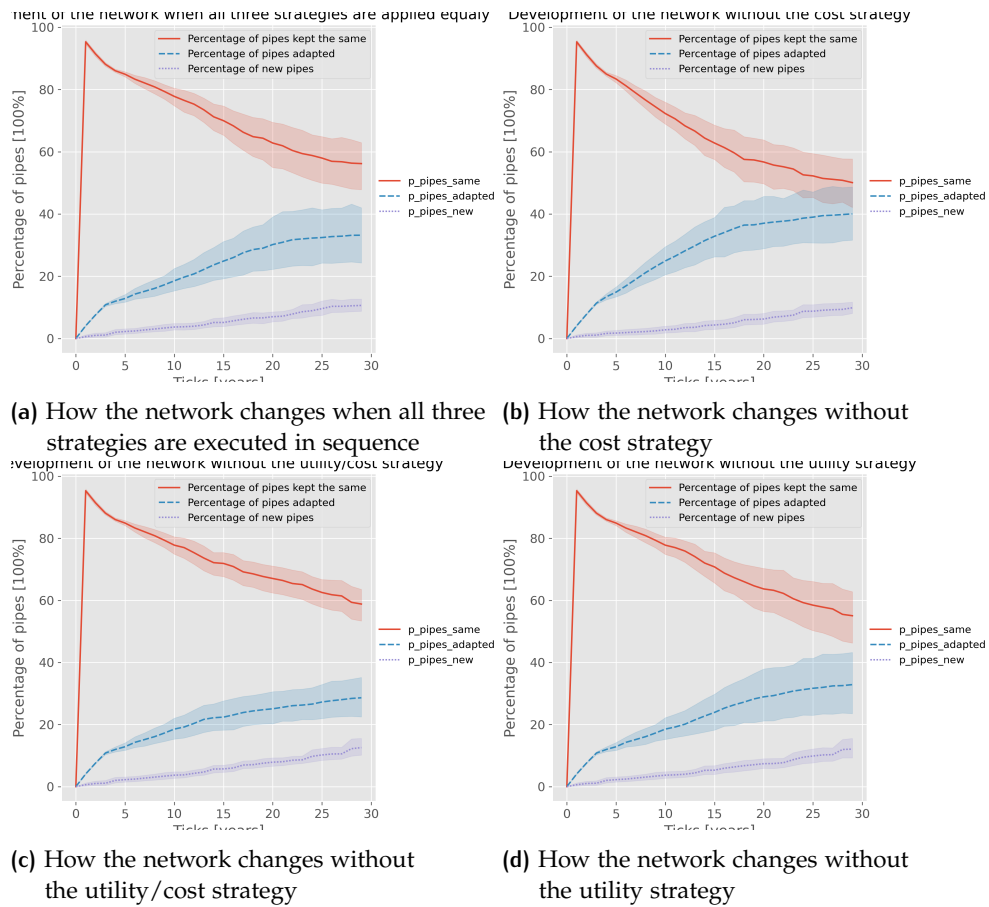


Figure H.3: Network development over time for experiment 1B

	all tree		skip cost		skip utility		skip utility/cost	
	tstat	pvalue	tstat	pvalue	tstat	pvalue	tstat	pvalue
all tree			-2,78	0,01	0,00	1,00	1,40	0,16
skip cost					2,69	0,01	4,53	1,67
skip utility							1,35	0,18
skip utility/cost								

Table H.6: Significance of the difference between the scenarios in experiment 1b in regard to the hydrogen export

	With corridor	
	tstat	pvalue
Without corridor	1,10	0,25

Table H.7: Significance of the difference between the scenarios in experiment 2 in regard to the costs

H.2 EXTRA RESULTS TACTIC OPTION 2

Two different scenarios are created in experiment 2. The threshold of $p = 0,05$ is used to determine the significance.

Tables [H.7](#), [H.8](#) and [H.9](#) indicate whether the difference between the scenarios is significant for the KPI costs, hydrogen delivery and hydrogen export. From these three tables, it can be deduced that the difference for the expenses in the different scenarios is not significant.

For the hydrogen delivery, the scenarios are also not significantly different. For the hydrogen export however, a significant difference is found in favour of the export corridor.

In regard to the centrality measures, no effect can be seen between the effectiveness of the corridor and the height of the centrality measure. This is shown for the KPI costs, hydrogen delivery and hydrogen export in figure [H.4](#)

	With corridor	
	tstat	pvalue
without corridor	-0,25	0,80

Table H.8: Significance of the difference between the scenarios in experiment 2 in regard to the hydrogen throughput

	With corridor	
	tstat	pvalue
without corridor	3,99	0,00

Table H.9: Significance of the difference between the scenarios in experiment 2 in regard to the hydrogen export

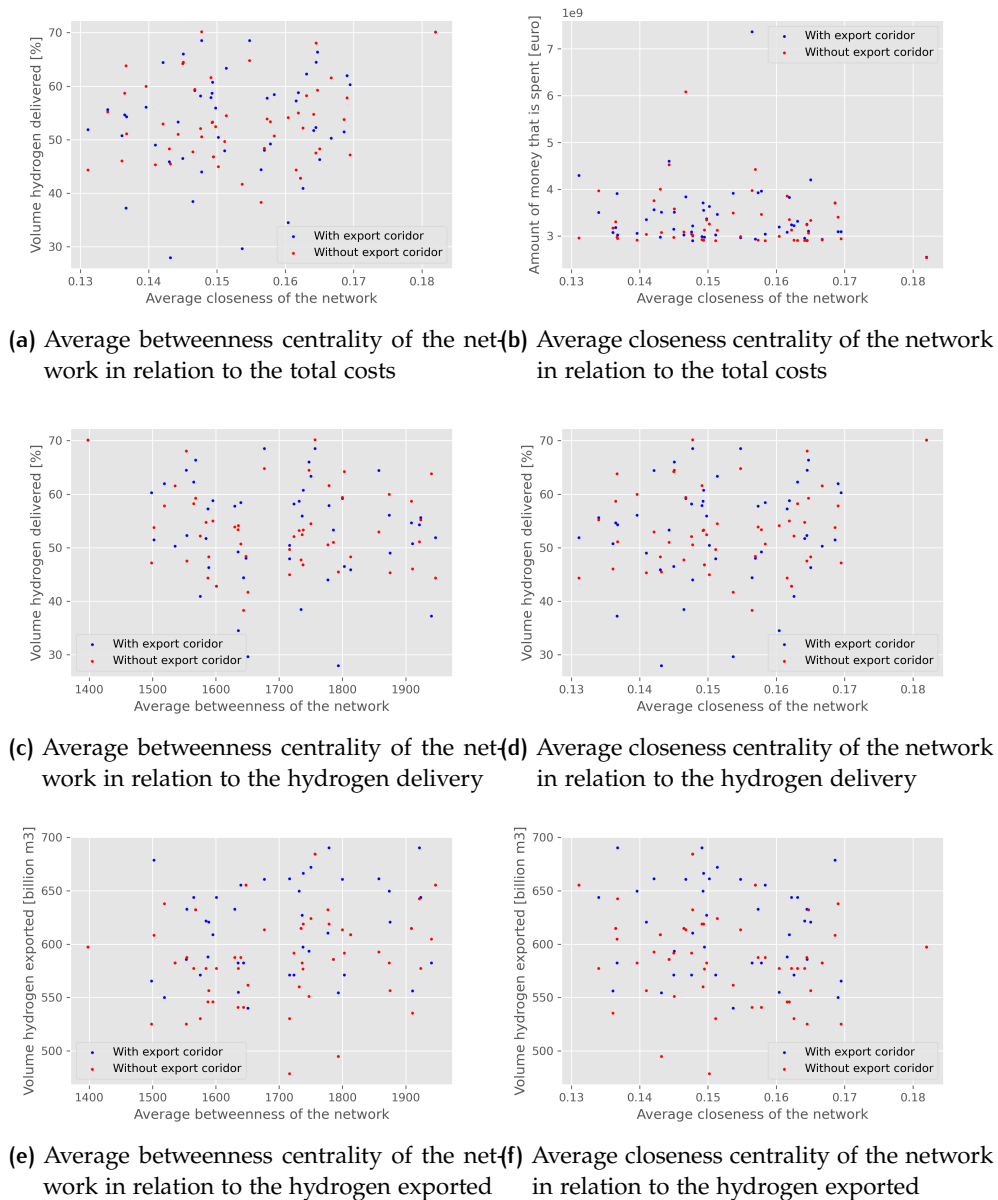


Figure H.4: Centrality measures in relation to the KPI's for tactic 2; the export corridor

H.3 EXTRA RESULTS TACTIC OPTION 3

Four different scenarios are created in experiment 3a. Tables [H.10](#), [H.11](#) and [H.12](#) indicate whether the difference between the scenarios is significant for the KPI costs, hydrogen delivery and hydrogen export. The threshold of $p = 0,05$ is used to determine the significance.

From these three tables, it can be deduced that scenario where no pipes are constructed under non of the conditions, is significantly the cheapest.

For the hydrogen delivery, the scenario where only pipes are constructed when it is included in the local optimisation process leads to a significant higher hydrogen delivery than all the other three scenarios.

None of the scenarios is significantly better for the hydrogen export.

	option pipe true, pipe for truck true		option pipe true, pipe for truck false		option pipe false, pipe for truck true		option pipe false, pipe for truck false	
	tstat	pvalue	tstat	pvalue	tstat	pvalue	tstat	pvalue
option pipe true, pipe for truck true			5,18	0,00	0,27	0,78	16,80	0,00
option pipe true, pipe for truck false					-3,11	0,00	23,75	0,00
option pipe false, pipe for truck true							11,66	0,00
option pipe false, pipe for truck false								

Table H.10: Significance of the difference between the scenarios in experiment 3a in regard to the costs

	option pipe true, pipe for truck true		option pipe true, pipe for truck false		option pipe false, pipe for truck true		option pipe false, pipe for truck false	
	tstat	pvalue	tstat	pvalue	tstat	pvalue	tstat	pvalue
option pipe true, pipe for truck true			-10,79	0,00	1,53	0,13	0,69	0,49
option pipe true, pipe for truck false					14,82	0,00	13,69	0,00
option pipe false, pipe for truck true							-0,94	0,35
option pipe false, pipe for truck false								

Table H.11: Significance of the difference between the scenarios in experiment 3a in regard to the hydrogen throughput

	option pipe true, pipe for truck true		option pipe true, pipe for truck false		option pipe false, pipe for truck true		option pipe false, pipe for truck false	
	tstat	pvalue	tstat	pvalue	tstat	pvalue	tstat	pvalue
option pipe true, pipe for truck true			-0,33	0,74	0,00	1,00	-0,33	0,74
option pipe true, pipe for truck false					-0,33	0,74	0,00	1,00
option pipe false, pipe for truck true							-0,33	0,74
option pipe false, pipe for truck false								

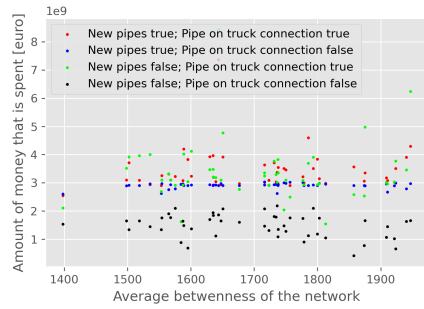
Table H.12: Significance of the difference between the scenarios in experiment 3a in regard to the hydrogen export

15 different scenarios are created in experiment 3a. Tables [H.13](#), [H.14](#) and [H.15](#) indicate whether the difference between the scenarios is significant for the KPI costs, hydrogen delivery and hydrogen export. The threshold of $p = 0,05$ is used to determine the significance.

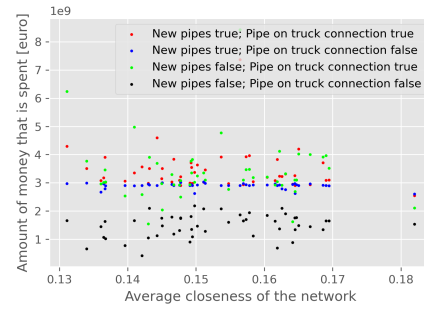
Only 6 scenarios are included in this analysis. From these three tables, it can be deduced that the scenarios are different in regard to costs and hydrogen throughput until at least 19 years. Between 19 and 29 years, the difference gets insignificant.

None of the scenarios is significantly different for the hydrogen export.

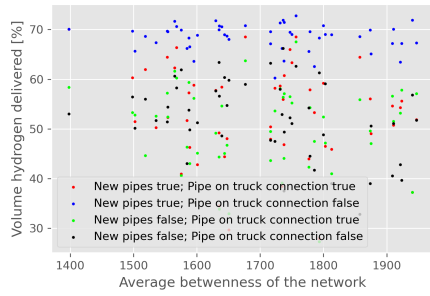
In regard to the centrality measures, no effect can be seen between the effectiveness of constructing new pipes and the height of the centrality measure. This is shown for the KPI costs, hydrogen delivery and hydrogen export in figure [H.5](#)



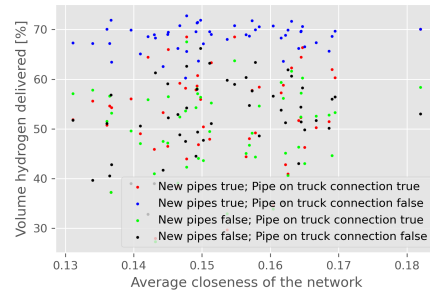
(a) Average betweenness centrality of the network in relation to the total costs



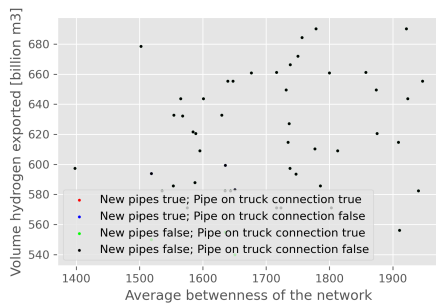
(b) Average closeness centrality of the network in relation to the total costs



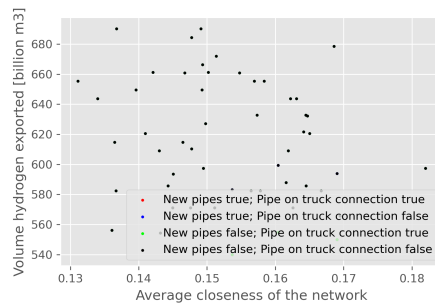
(c) Average betweenness centrality of the network in relation to the hydrogen delivery



(d) Average closeness centrality of the network in relation to the hydrogen delivery



(e) Average betweenness centrality of the network in relation to the hydrogen exported



(f) Average closeness centrality of the network in relation to the hydrogen exported

Figure H.5: Centrality measures in relation to the KPI's for tactic 3a; the construction of new pipes

	1 year		3 years		5 years		9 years		19 years		29 years	
	tstat	pvalue	tstat	pvalue	tstat	pvalue	tstat	pvalue	tstat	pvalue	tstat	pvalue
1 year			3,91	0,00	4,31	0,00	5,30	0,00	6,14	0,00	6,18	0,00
3 years					0,73	0,47	2,81	0,01	5,02	0,00	5,15	0,00
5 years							2,07	0,00	4,46	0,00	4,60	0,00
9 years									4,72	0,00	5,06	0,00
19 years											0,88	0,38
29 years												

Table H.13: Significance of the difference between the scenarios in experiment 3b in regard to the costs

	1 year		3 years		5 years		9 years		19 years		29 years	
	tstat	pvalue	tstat	pvalue	tstat	pvalue	tstat	pvalue	tstat	pvalue	tstat	pvalue
1 year			-8,48	0,00	-15,80	0,00	-20,12	0,00	-25,05	0,00	-25,31	0,00
3 years					-3,82	0,00	-6,50	0,00	-8,93	0,00	-9,09	0,00
5 years							-3,40	0,00	-6,70	0,00	-6,93	0,00
9 years									-3,20	0,00	-3,45	0,00
19 years											-0,29	0,77
29 years												

Table H.14: Significance of the difference between the scenarios in experiment 3b in regard to the hydrogen delivery

	1 year		3 years		5 years		9 years		19 years		29 years	
	tstat	pvalue	tstat	pvalue	tstat	pvalue	tstat	pvalue	tstat	pvalue	tstat	pvalue
1 year			1,424	0,15	-1,81	0,07	-1,81	0,07	-1,80	0,07	6,18	1,44
3 years					-0,33	0,74	-0,33	0,74	-0,33	0,74	-0,33	0,74
5 years							0,00	1,00	0,00	1,00	0,00	1,00
9 years									0,00	1,00	0,00	1,00
19 years											0,00	1,00
29 years												

Table H.15: Significance of the difference between the scenarios in experiment 3b in regard to the costs

H.4 EXTRA RESULTS TACTIC OPTION 4

Three different scenarios are created in experiment 3a. Tables [H.16](#), [H.17](#) and [H.18](#) indicate whether the difference between the scenarios is significant for the KPI costs, hydrogen delivery and hydrogen export. The threshold of $p = 0,05$ is used to determine the significance.

From these three tables, it can be deduced that the scenario where the budget is allocated increasingly are decreasingly are significantly different in regard to all three KPI's. Additionally, there is a significant difference in regard to the hydrogen export between the scenario where the budget is allocated equally or increasingly. The p-value for the difference between the scenario where the budget is allocated equal or decreasing is 0,07, so not significant, but close.

For the hydrogen delivery, the scenario where only pipes are constructed when it is included in the local optimisation process leads to a significant higher hydrogen delivery than all the other three scenarios.

None of the scenarios is significantly better for the hydrogen export.

	equal		increasing		decreasing	
	tstat	pvalue	tstat	pvalue	tstat	pvalue
equal			-1,69	0,09	1,32	0,19
increasing					2,58	0,01
decreasing						

Table H.16: Significance of the difference between the scenarios in experiment 4 in regard to the costs

	equal		increasing		decreasing	
	tstat	pvalue	tstat	pvalue	tstat	pvalue
equal			7,44	3,82	-6,13	1,59
increasing					2,58	0,01
decreasing						

Table H.17: Significance of the difference between the scenarios in experiment 4 in regard to the hydrogen delivery

	equal		increasing		decreasing	
	tstat	pvalue	tstat	pvalue	tstat	pvalue
equal			7,54	0,00	-1,82	0,07
increasing					-10,08	0,00
decreasing						

Table H.18: Significance of the difference between the scenarios in experiment 4 in regard to the hydrogen export

The plots in figure [H.6](#) show that the three different tactical options show a different development over time. Even though the costs end up in the same range, the process is different. For the hydrogen delivery, a clear effect can be seen.

In regard to the centrality measures, no effect can be seen between the effectiveness of constructing new pipes and the height of the centrality measure. This is shown for the KPI costs, hydrogen delivery and hydrogen export in figure [H.7](#)

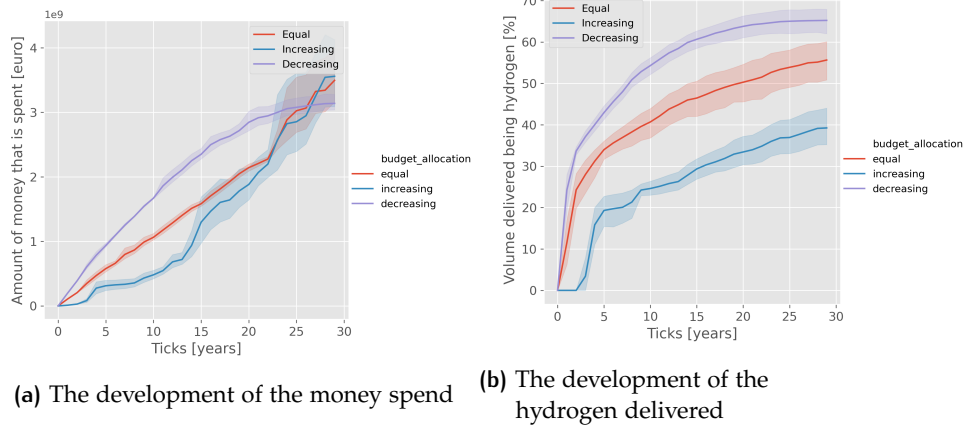


Figure H.6: Development over time for experiment 4

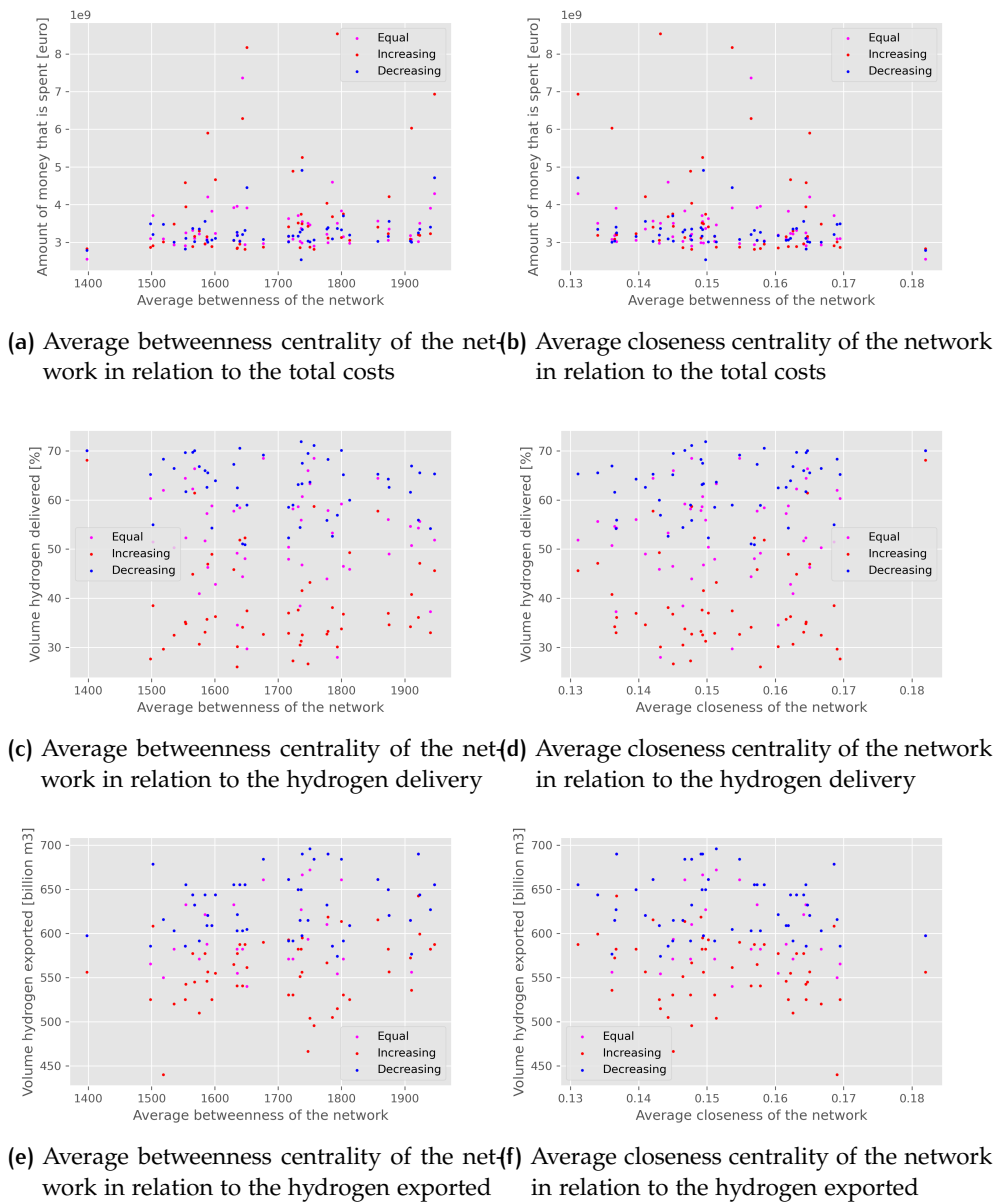


Figure H.7: Centrality measures in relation to the KPI's for tactic 4; the budget allocation

I | EXTRA RESULTS FOR THE STRATEGIES

I.1 COMPARISON OF THE FOUR STRATEGIES

In figure I.1 the volume hydrogen delivered is shown over time. The sharp increases in the volume hydrogen in the strategy where the hydrogen delivery is maximised, but where no corridor is active, can be explained by the fact when the corridor is active, significant investments for the corridor are made in the beginning. With this, a big portion of the hydrogen demand, which is the export of hydrogen, is connected in the beginning. Without the corridor, these investments are not bounded by a specific moment, and those sharp increases are seen when the specific connection to a hydrogen export point is made.

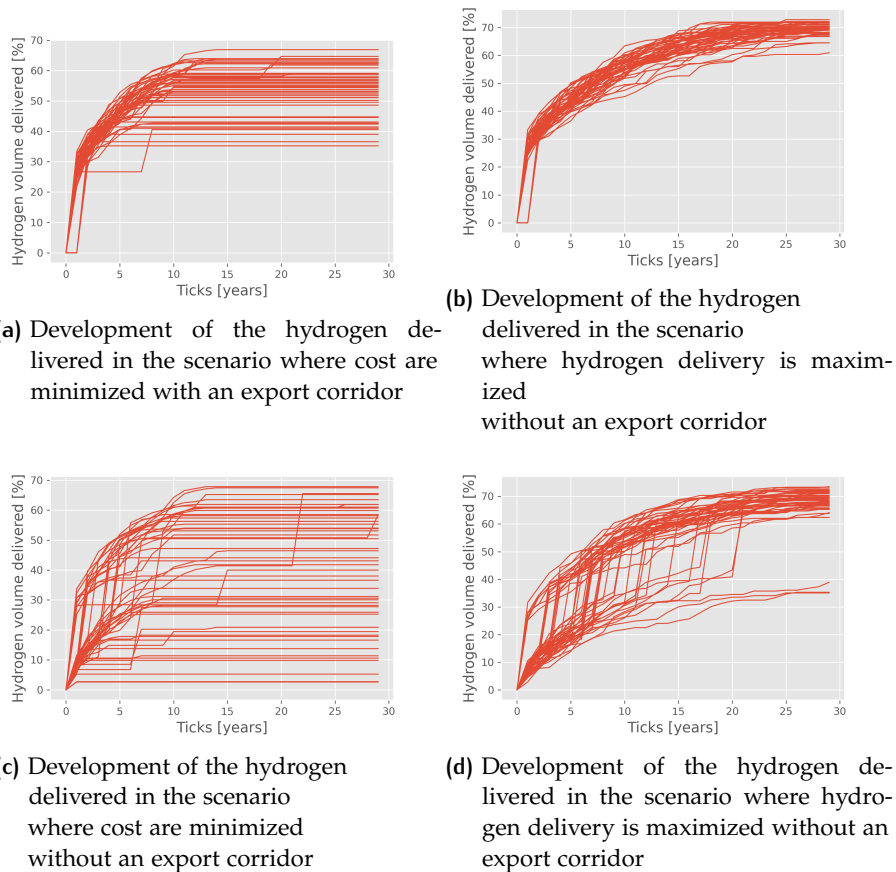


Figure I.1: Development of the % hydrogen volume delivered in the four overarching scenarios

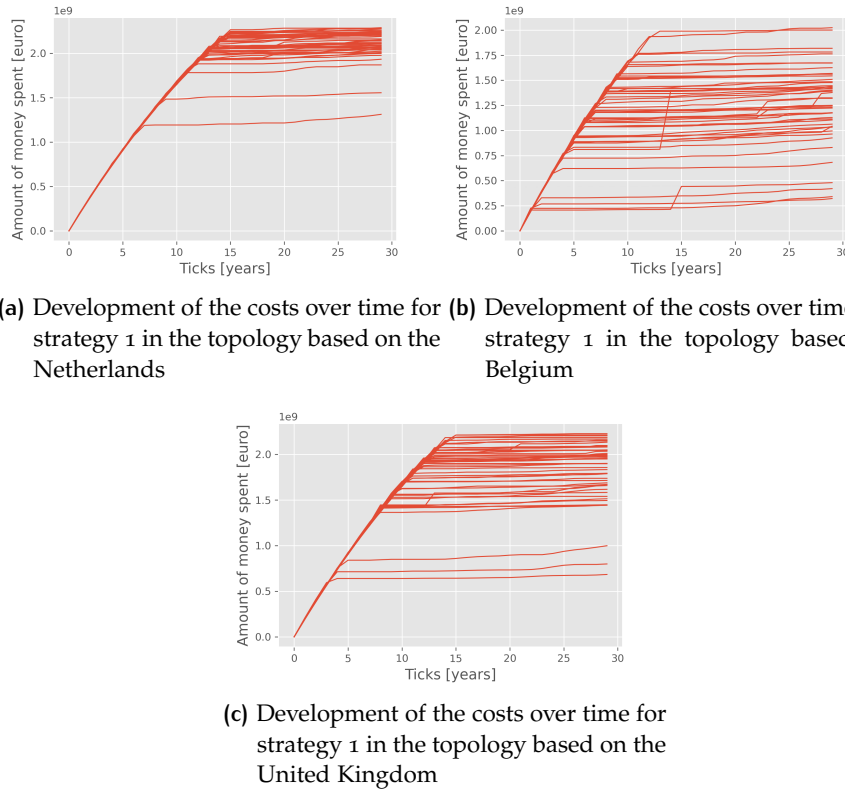


Figure I.2: Development of the costs over time for strategy 1 in the three different country based topologies

	Random		Netherlands		Belgium		UK	
	tstat	pvalue	tstat	pvalue	tstat	pvalue	tstat	pvalue
Random			-11,10	0,00	1,71	0,89	-5,52	0,00
Netherlands					14,04	0,00	5,28	0,00
Belgium							-7,63	0,00
UK								

Table I.1: Significance of the difference between the scenarios for strategy 1 in regard to the expenses

I.2 EXTRA RESULTS STRATEGY 1: MINIMIZE COST WITH HYDROGEN CORRIDOR

In the plots I.2 it is shown how the lock-in effect occurs for the different countries at different moments in time.

Table I.1, table I.2 and table I.3 show whether the different impact of strategy 1 is significantly different in the different topologies. For the expenses and the hydrogen delivery this is the case (in most situations). The hydrogen export is however not significantly different.

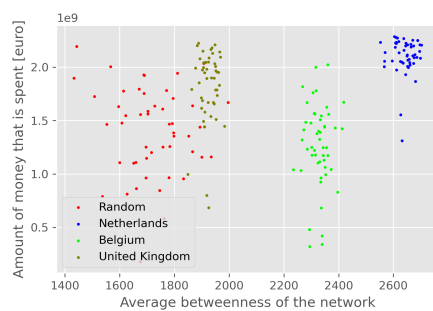
In regard to the centrality measures, no effect can be seen between the effectiveness of strategy 1 and the different centrality's. This is shown for the KPI costs, hydrogen delivery and hydrogen export in figure I.3

	Random		Netherlands		Belgium		UK	
	tstat	pvalue	tstat	pvalue	tstat	pvalue	tstat	pvalue
Random			-11,80	0,00	0,28	0,78	-6,16	0,00
Netherlands					12,01	0,00	3,89	0,00
Belgium							-6,39	0,00
UK								

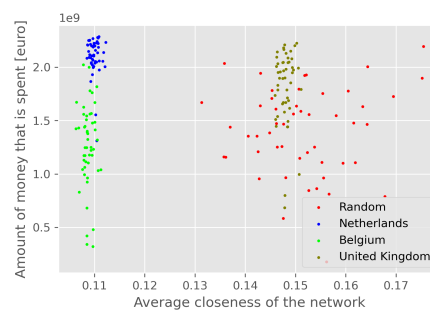
Table I.2: Significance of the difference between the scenarios for strategy 1 in regard to the hydrogen delivery

	Random		Netherlands		Belgium		UK	
	tstat	pvalue	tstat	pvalue	tstat	pvalue	tstat	pvalue
Random			-0,90	0,36	-0,85	0,40	0,28	0,78
Netherlands					0,00	1,00	1,21	0,23
Belgium							1,13	0,26
UK								

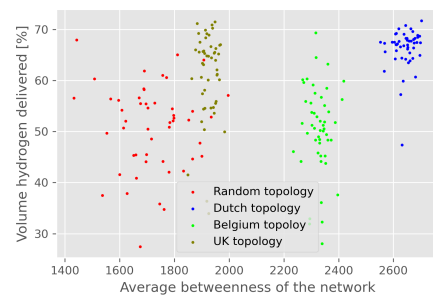
Table I.3: Significance of the difference between the scenarios for strategy 1 in regard to the hydrogen export



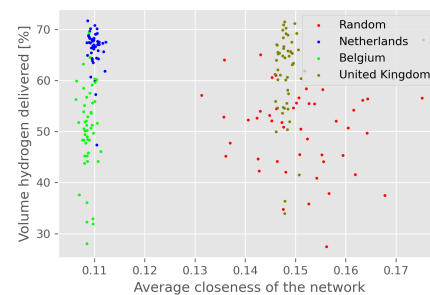
(a) Average betweenness centrality of the network in relation to the total costs



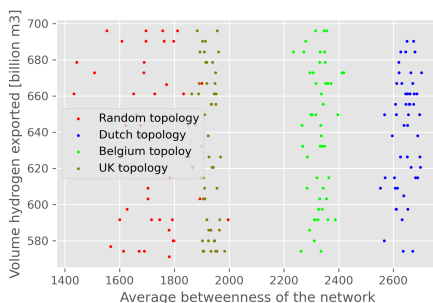
(b) Average closeness centrality of the network in relation to the total costs



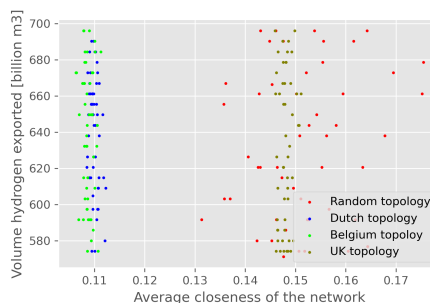
(c) Average betweenness centrality of the network in relation to the hydrogen delivery



(d) Average closeness centrality of the network in relation to the hydrogen delivery



(e) Average betweenness centrality of the network in relation to the hydrogen exported



(f) Average closeness centrality of the network in relation to the hydrogen exported

Figure I.3: Centrality measures in relation to the KPI's for strategy 1

	Random		Netherlands		Belgium		UK	
	tstat	pvalue	tstat	pvalue	tstat	pvalue	tstat	pvalue
Random			3,73	0,00	5,46	0,00	6,11	0,00
Netherlands					9,34	0,00	1,88	0,06
Belgium							-9,69	0,00
UK								

Table I.4: Significance of the difference between the scenarios for strategy 2 in regard to the expenses

	Random		Netherlands		Belgium		UK	
	tstat	pvalue	tstat	pvalue	tstat	pvalue	tstat	pvalue
Random			2,80	0,01	16,11	0,00	2,33	0,02
Netherlands					7,59	0,00	-0,47	0,00
Belgium							-10,00	0,00
UK								

Table I.5: Significance of the difference between the scenarios for strategy 2 in regard to the hydrogen delivery

I.3 EXTRA RESULTS STRATEGY 2: MINIMIZE COST WITHOUT HYDROGEN CORRIDOR

Table I.4, table I.5 and table I.6 show whether the different impact of strategy 2 is significantly different in the different topologies. This is the case for the expenses, the hydrogen delivery and the hydrogen export.

	Random		Netherlands		Belgium		UK	
	tstat	pvalue	tstat	pvalue	tstat	pvalue	tstat	pvalue
Random			2,34	0,02	9,50	0,00	-2,91	0,00
Netherlands					3,83	0,00	-4,12	0,00
Belgium							-7,44	0,00
UK								

Table I.6: Significance of the difference between the scenarios for strategy 2 in regard to the hydrogen export

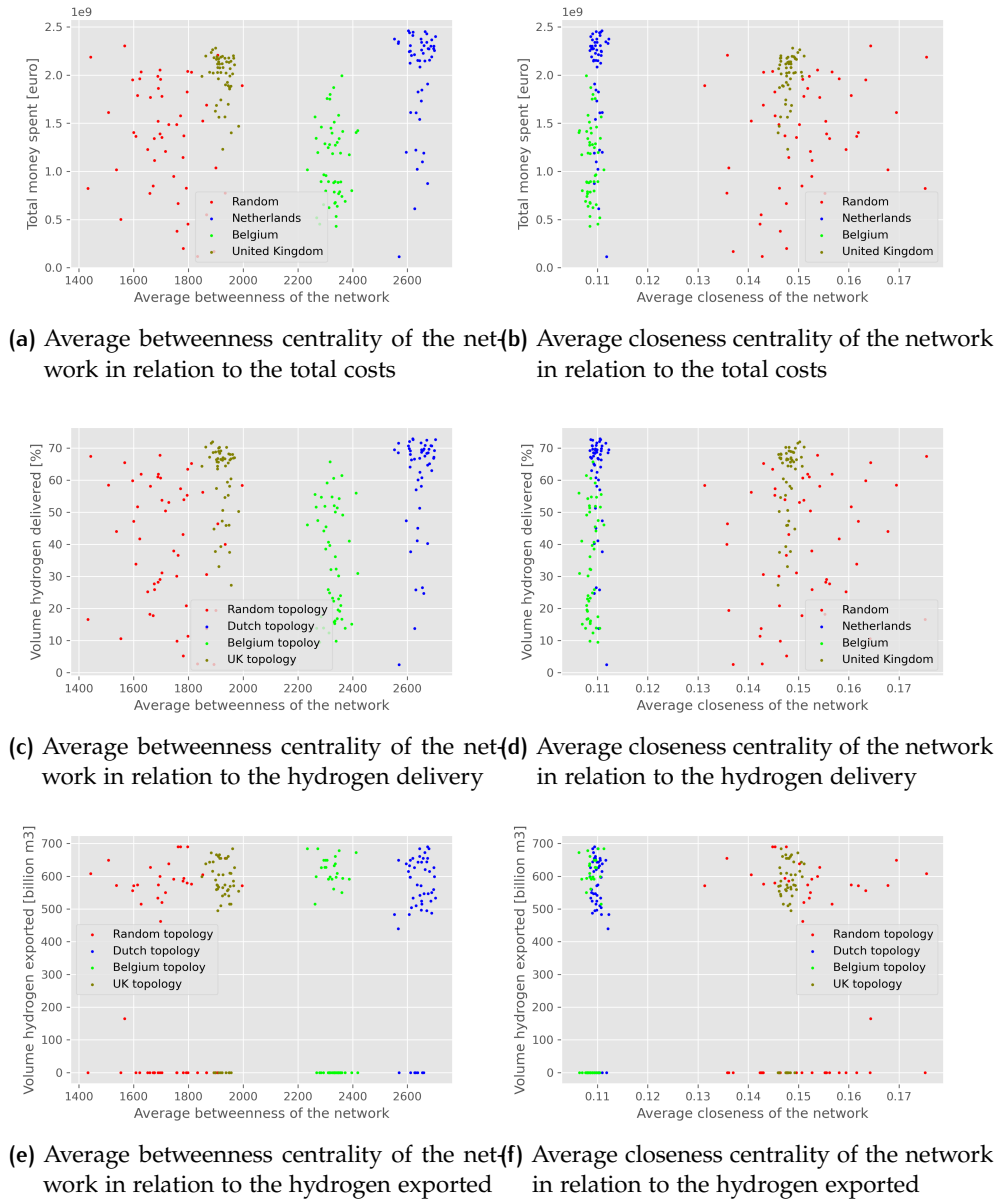


Figure I.4: Centrality measures in relation to the KPI's for strategy 2

In regard to the centrality measures, no effect can be seen between the effectiveness of strategy 2 and the different centrality's. This is shown for the KPI costs, hydrogen delivery and hydrogen export in figure I.4

I.4 EXTRA RESULTS STRATEGY 3: MAXIMIZE HYDROGEN DELIVERY WITH HYDROGEN CORRIDOR

Table I.7, table I.8 and table I.9 show whether the different impact of strategy 3 is significantly different in the different topologies. For the expenses and the hydrogen delivery this is the case (in most situations). The hydrogen export is however only the random network is significantly different from the other topologies.

	Random		Netherlands		Belgium		UK	
	tstat	pvalue	tstat	pvalue	tstat	pvalue	tstat	pvalue
Random			-5,43	0,00	-7,99	0,00	-3,43	0,00
Netherlands					-5,83	0,00	3,93	0,00
Belgium							8,47	0,00
UK								

Table I.7: Significance of the difference between the scenarios for strategy 3 in regard to the expenses

	Random		Netherlands		Belgium		UK	
	tstat	pvalue	tstat	pvalue	tstat	pvalue	tstat	pvalue
Random			-3,59	0,00	-2,97	0,00	-3,38	0,00
Netherlands					3,36	0,00	1,39	0,17
Belgium							-2,00	0,05
UK								

Table I.8: Significance of the difference between the scenarios for strategy 3 in regard to the hydrogen delivery

	Random		Netherlands		Belgium		UK	
	tstat	pvalue	tstat	pvalue	tstat	pvalue	tstat	pvalue
Random			-3,26	0,00	-3,29	0,00	-2,91	0,00
Netherlands					-0,12	0,91	1,09	0,28
Belgium							1,13	0,26
UK								

Table I.9: Significance of the difference between the scenarios for strategy 3 in regard to the hydrogen export

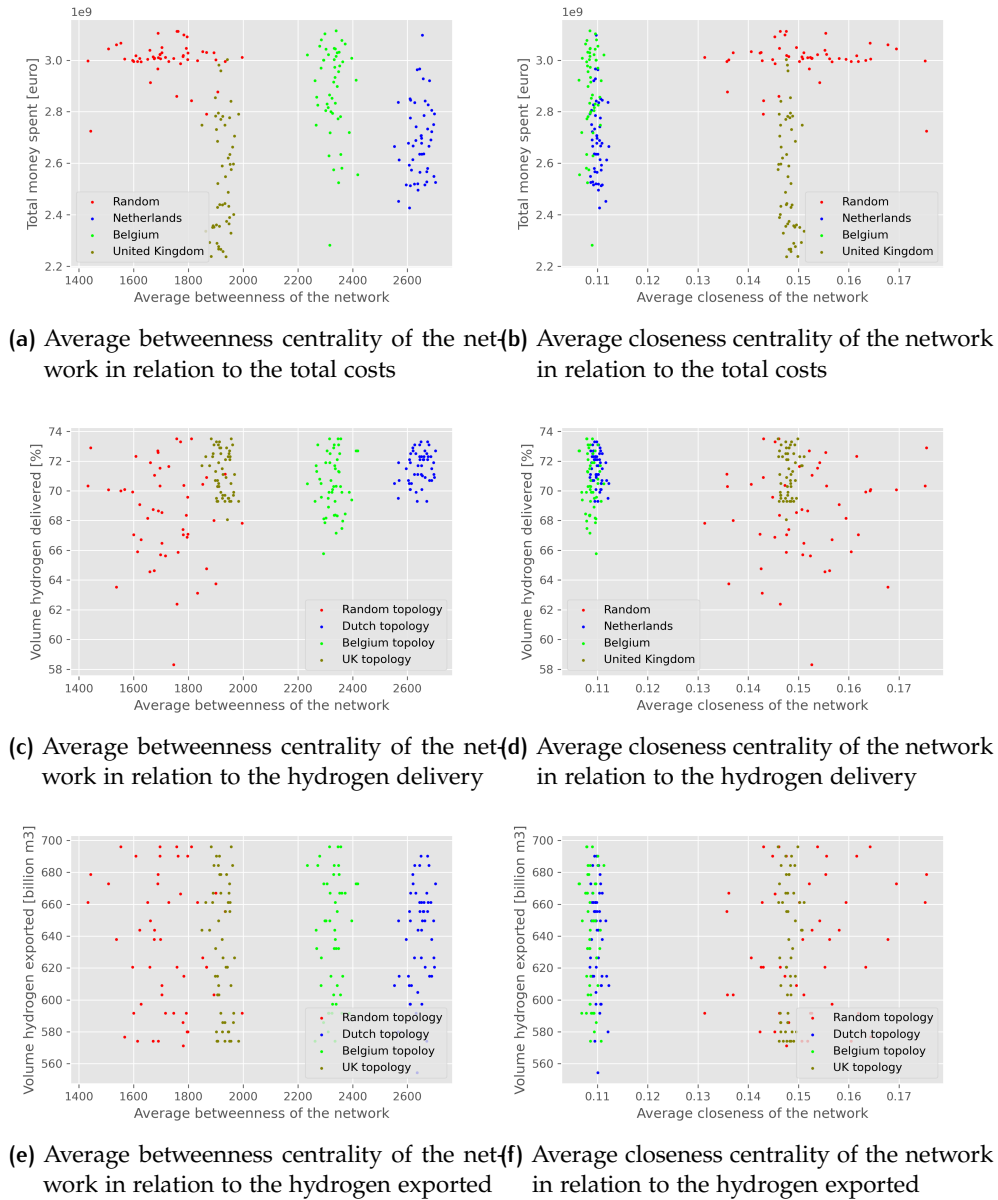


Figure I.5: Centrality measures in relation to the KPI's for strategy 3

In regard to the centrality measures, no effect can be seen between the effectiveness of strategy 3 and the different centrality's. This is shown for the KPI costs, hydrogen delivery and hydrogen export in figure I.5

I.5 EXTRA RESULTS STRATEGY 4: MAXIMIZE HYDROGEN DELIVERY WITHOUT HYDROGEN CORRIDOR

Table I.10, table I.11 and table I.12 show whether the different impact of strategy 4 is significantly different in the different topologies. For the expenses this is the case (in most situations). The hydrogen delivery and is however not significantly different. Only in some cases, the hydrogen export has significantly different outcomes for the different topologies.

	Random		Netherlands		Belgium		UK	
	tstat	pvalue	tstat	pvalue	tstat	pvalue	tstat	pvalue
Random			-6,43	0,00	-8,29	0,00	-2,89	0,00
Netherlands					-4,03	0,00	6,71	0,00
Belgium							11,56	0,00
UK								

Table I.10: Significance of the difference between the scenarios for strategy 4 in regard to the expenses

	Random		Netherlands		Belgium		UK	
	tstat	pvalue	tstat	pvalue	tstat	pvalue	tstat	pvalue
Random			-3,01		2,69	0,01	-3,38	
Netherlands					0,87	0,39	-0,84	0,40
Belgium							-1,91	0,06
UK								

Table I.11: Significance of the difference between the scenarios for strategy 4 in regard to the hydrogen delivery

	Random		Netherlands		Belgium		UK	
	tstat	pvalue	tstat	pvalue	tstat	pvalue	tstat	pvalue
Random			2,45	0,01	5,38	1,17	1,41	0,16
Netherlands					2,15	0,03	-0,98	0,33
Belgium							-2,93	0,00
UK								

Table I.12: Significance of the difference between the scenarios for strategy 4 in regard to the hydrogen export

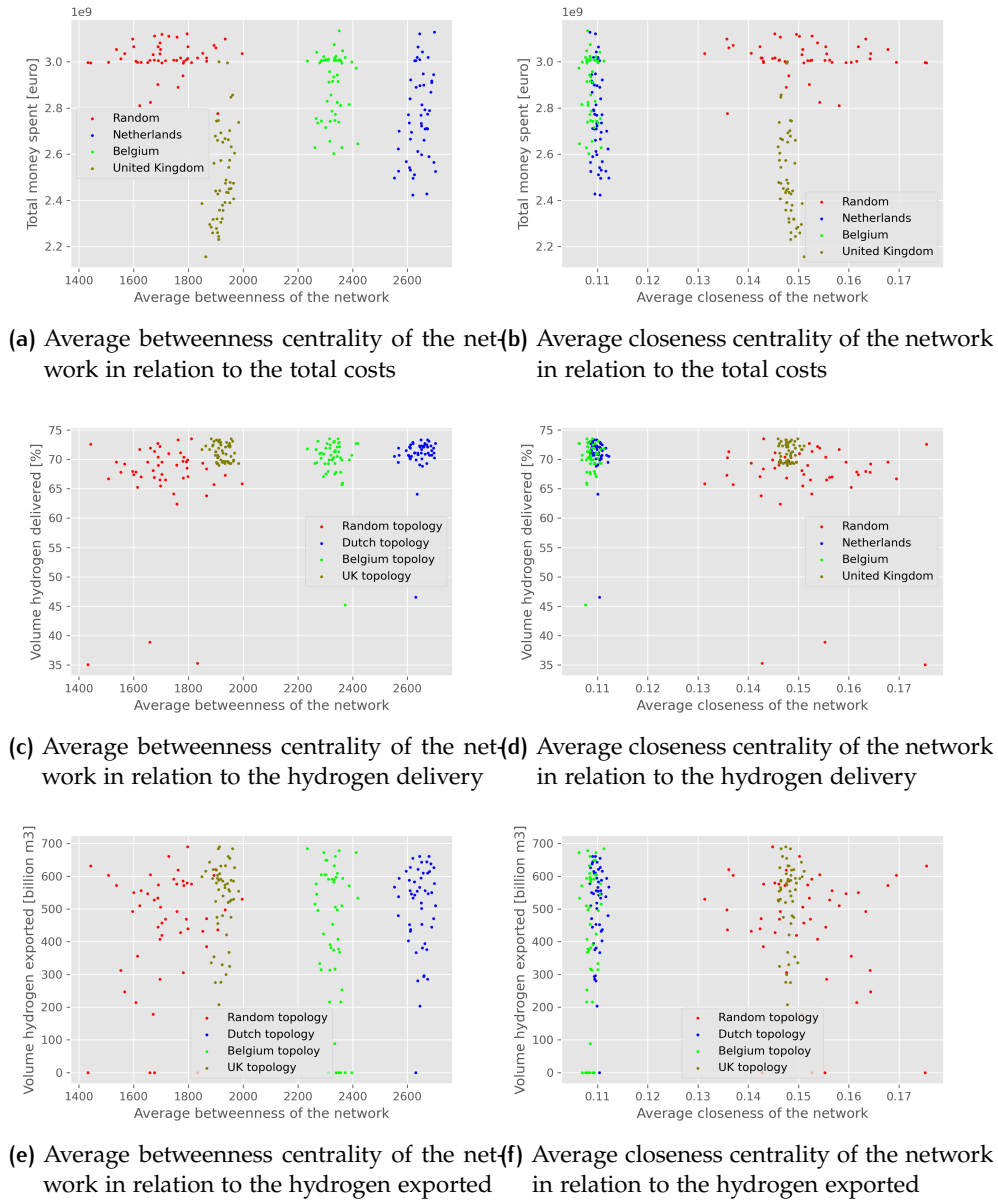


Figure I.6: Centrality measures in relation to the KPI's for strategy 4

In regard to the centrality measures, no effect can be seen between the effectiveness of strategy 4 and the different centrality's. This is shown for the KPI costs, hydrogen delivery and hydrogen export in figure I.6

I.6 EXTRA RESULTS FOR THE DUTCH BASED TOPOLOGY

Table I.13, table I.14 and table I.15 show whether the different strategies have a significantly different effect in the topology based on the Netherlands. This is the case for almost all values.

	Costs, export corridor		costs, no export corridor		Hydrogen delivery, export corridor		Hydrogen delivery, no export corridor	
	tstat	pvalue	tstat	pvalue	tstat	pvalue	tstat	pvalue
Costs, export corridor			1,42	0,16	-18,05	0,00	-17,97	0,00
costs, no export corridor					-8,77	0,00	-9,50	0,00
Hydrogen delivery, export corridor							-2,20	0,03
Hydrogen delivery, no export corridor							height	

Table I.13: Significance of the difference between the strategies for topology based on the Netherlands in regard to the expenses

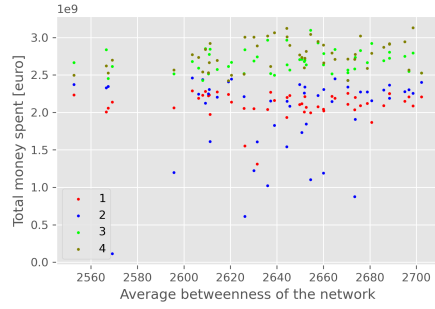
	Costs, export corridor		costs, no export corridor		Hydrogen delivery, export corridor		Hydrogen delivery, no export corridor	
	tstat	pvalue	tstat	pvalue	tstat	pvalue	tstat	pvalue
Costs, export corridor			2,61	0,01	-9,20	0,00	-5,72	0,00
costs, no export corridor					-4,88	0,00	-4,42	0,00
Hydrogen delivery, export corridor							1,51	0,14
Hydrogen delivery, no export corridor							height	

Table I.14: Significance of the difference between the strategies for topology based on the Netherlands in regard to the hydrogen delivery

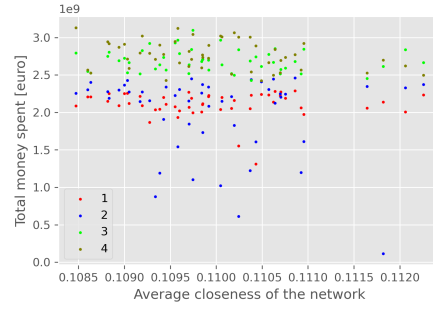
	Costs, export corridor		costs, no export corridor		Hydrogen delivery, export corridor		Hydrogen delivery, no export corridor	
	tstat	pvalue	tstat	pvalue	tstat	pvalue	tstat	pvalue
Costs, export corridor			4,44	0,00	0,14	0,89	6,89	0,00
costs, no export corridor					-4,41	0,00	-0,02	0,99
Hydrogen delivery, export corridor							6,84	0,00
Hydrogen delivery, no export corridor							height	

Table I.15: Significance of the difference between the strategies for topology based on the Netherlands in regard to the hydrogen export

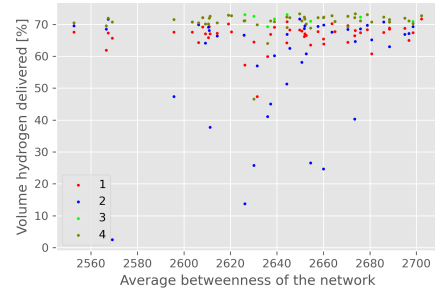
In regard to the centrality measures, no effect can be seen between the effectiveness of the strategies and the different centrality's. This is shown for the KPI costs, hydrogen delivery and hydrogen export in figure I.7



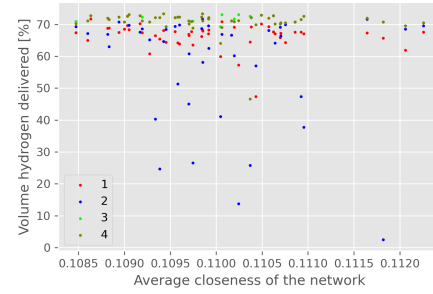
(a) Average betweenness centrality of the network in relation to the total costs



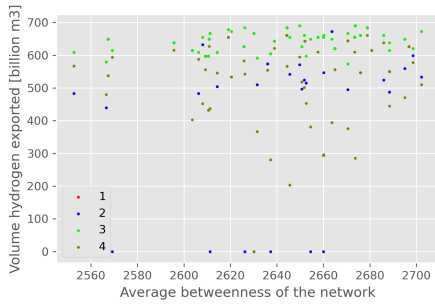
(b) Average closeness centrality of the network in relation to the total costs



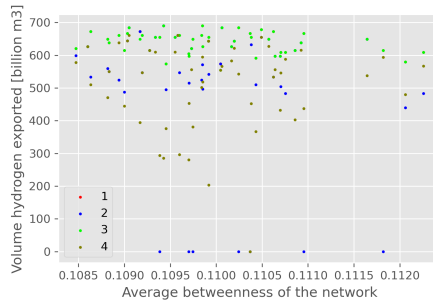
(c) Average betweenness centrality of the network in relation to the hydrogen delivery



(d) Average closeness centrality of the network in relation to the hydrogen delivery



(e) Average betweenness centrality of the network in relation to the hydrogen exported



(f) Average closeness centrality of the network in relation to the hydrogen exported

Figure I.7: Centrality measures in relation to the KPI's for the topology based on the Netherlands

I.7 EXTRA RESULTS FOR THE BELGIUM BASED TOPOLOGY

Table I.16, table I.17 and table I.18 show whether the different strategies have a significantly different effect in the topology based on Belgium. This is the case for almost all values. Only strategy 3 and 4 are not significantly different in regard to expenses and hydrogen delivery.

	Costs, export corridor		costs, no export corridor		Hydrogen delivery, export corridor		Hydrogen delivery, no export corridor	
	tstat	pvalue	tstat	pvalue	tstat	pvalue	tstat	pvalue
Costs, export corridor	2,11	0,04			-26,86	0,00	-28,61	0,00
costs, no export corridor					-28,61	0,00	-29,89	0,00
Hydrogen delivery, export corridor							-0,64	0,52
Hydrogen delivery, no export corridor								

Table I.16: Significance of the difference between the strategies for topology based on Belgium in regard to the expenses

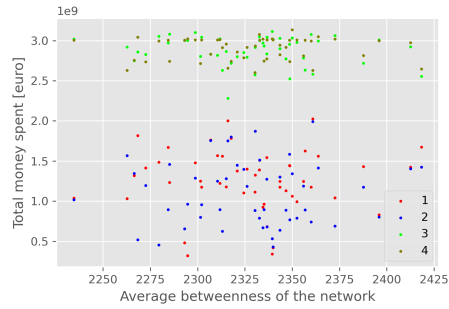
	Costs, export corridor		costs, no export corridor		Hydrogen delivery, export corridor		Hydrogen delivery, no export corridor	
	tstat	pvalue	tstat	pvalue	tstat	pvalue	tstat	pvalue
Costs, export corridor	5,93	0,00			-16,22	0,00	-14,65	0,00
costs, no export corridor					-14,93	0,00	-14,41	0,00
Hydrogen delivery, export corridor							-0,74	0,46
Hydrogen delivery, no export corridor								

Table I.17: Significance of the difference between the strategies for topology based on Belgium in regard to the hydrogen delivery

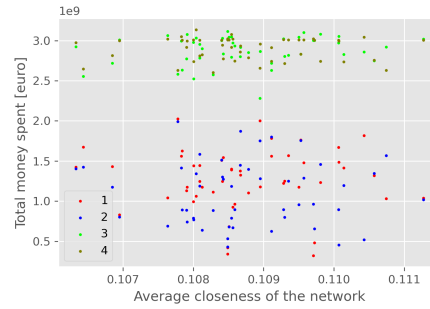
	Costs, export corridor		costs, no export corridor		Hydrogen delivery, export corridor		Hydrogen delivery, no export corridor	
	tstat	pvalue	tstat	pvalue	tstat	pvalue	tstat	pvalue
Costs, export corridor	7,65	0,00			0,00	1,00	6,77	0,00
costs, no export corridor					-7,65	0,00	-2,30	0,02
Hydrogen delivery, export corridor							6,77	0,00
Hydrogen delivery, no export corridor								

Table I.18: Significance of the difference between the strategies for topology based on Belgium in regard to the hydrogen export

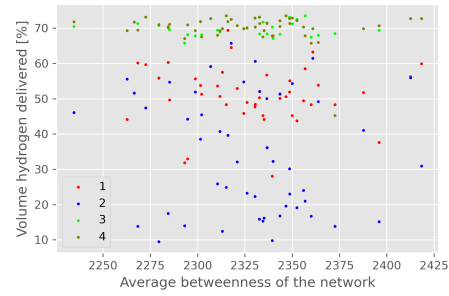
In regard to the centrality measures, no effect can be seen between the effectiveness of the strategies and the different centrality's. This is shown for the KPI costs, hydrogen delivery and hydrogen export in figure I.8



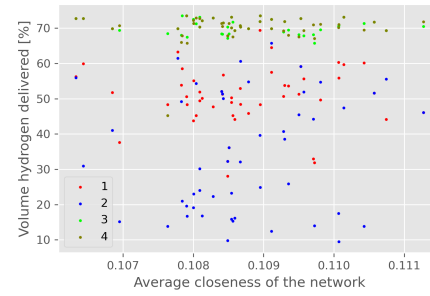
(a) Average betweenness centrality of the network in relation to the total costs



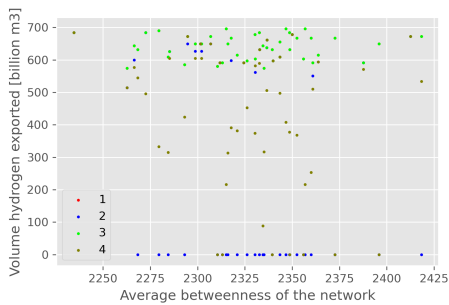
(b) Average closeness centrality of the network in relation to the total costs



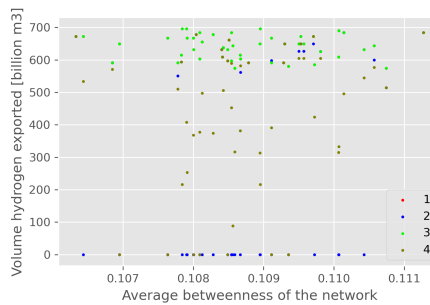
(c) Average betweenness centrality of the network in relation to the hydrogen delivery



(d) Average closeness centrality of the network in relation to the hydrogen delivery



(e) Average betweenness centrality of the network in relation to the hydrogen exported



(f) Average closeness centrality of the network in relation to the hydrogen exported

Figure I.8: Centrality measures in relation to the KPI's for the topology based in Belgium

I.8 EXTRA RESULTS FOR THE TOPOLOGY BASED ON THE UNITED KINGDOM

Table I.19, table I.20 and table I.21 show whether the different strategies have a significantly different effect in the topology based on the United Kingdom. This is the case for almost all values. Only strategy 3 and 4 are not significantly different in regard to expenses and hydrogen delivery. The strategies with and without corridor are also not significantly different.

	Costs, export corridor		costs, no export corridor		Hydrogen delivery, export corridor		Hydrogen delivery, no export corridor	
	tstat	pvalue	tstat	pvalue	tstat	pvalue	tstat	pvalue
Costs, export corridor			-2,85	0,01	-1,75	0,00	-12,18	0,00
costs, no export corridor					-12,01	0,00	-11,60	0,00
Hydrogen delivery, export corridor							0,96	0,34
Hydrogen delivery, no export corridor								

Table I.19: Significance of the difference between the strategies for topology based on the United Kingdom in regard to the expenses

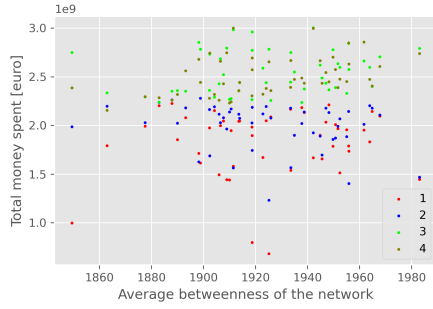
	Costs, export corridor		costs, no export corridor		Hydrogen delivery, export corridor		Hydrogen delivery, no export corridor	
	tstat	pvalue	tstat	pvalue	tstat	pvalue	tstat	pvalue
Costs, export corridor	0,31	0,76			-8,24	0,00	-8,25	0,00
costs, no export corridor					-6,57	0,00	-6,57	0,00
Hydrogen delivery, export corridor							-0,02	0,98
Hydrogen delivery, no export corridor								

Table I.20: Significance of the difference between the strategies for topology based on the United Kingdom in regard to the hydrogen delivery

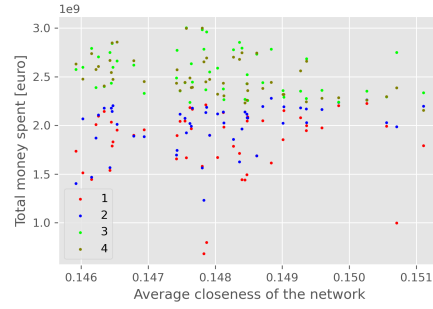
	Costs, export corridor		costs, no export corridor		Hydrogen delivery, export corridor		Hydrogen delivery, no export corridor	
	tstat	pvalue	tstat	pvalue	tstat	pvalue	tstat	pvalue
Costs, export corridor			4,19	0,00	0,00	1,00	5,63	0,00
costs, no export corridor					-4,19	0,00	-0,08	0,28
Hydrogen delivery, export corridor							5,63	0,00
Hydrogen delivery, no export corridor								

Table I.21: Significance of the difference between the strategies for topology based on the United Kingdom in regard to the hydrogen export

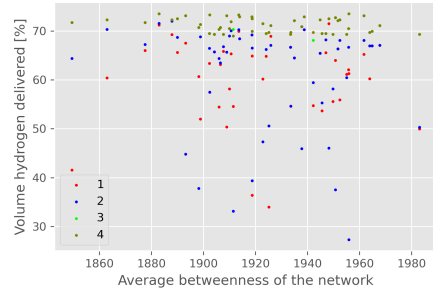
In regard to the centrality measures, no effect can be seen between the effectiveness of the strategies and the different centrality's. This is shown for the KPI costs, hydrogen delivery and hydrogen export in figure I.9



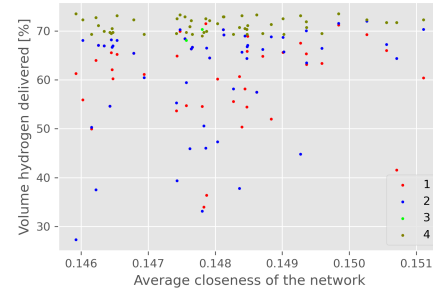
(a) Average betweenness centrality of the network in relation to the total costs



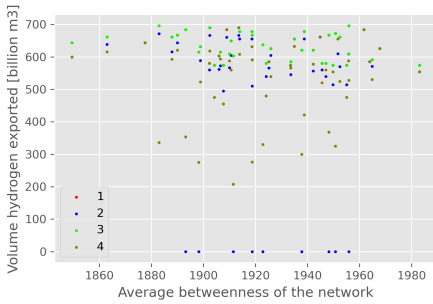
(b) Average closeness centrality of the network in relation to the total costs



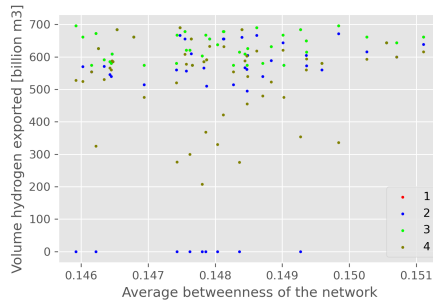
(c) Average betweenness centrality of the network in relation to the hydrogen delivery



(d) Average closeness centrality of the network in relation to the hydrogen delivery



(e) Average betweenness centrality of the network in relation to the hydrogen exported



(f) Average closeness centrality of the network in relation to the hydrogen exported

Figure I.9: Centrality measures in relation to the KPI's for the topology based in Belgium

I.9 EXTRA RESULTS FOR THE RANDOM TOPOLOGY

Table ??, table ?? and table ?? show whether the different strategies have a significantly different effect in the random topology. In regard to the hydrogen export, all strategies are significantly different.

	Costs, export corridor		costs, no export corridor		Hydrogen delivery, export corridor		Hydrogen delivery, no export corridor	
	tstat	pvalue	tstat	pvalue	tstat	pvalue	tstat	pvalue
Costs, export corridor			4,52	0,00	-1,88	0,06	-4,76	0,00
costs, no export corridor					-4,54	0,00	-7,28	0,00
Hydrogen delivery, export corridor							-1,84	0,07
Hydrogen delivery, no export corridor								

Table I.22: Significance of the difference between the strategies in the random topology in regard to the expenses

	Costs, export corridor		costs, no export corridor		Hydrogen delivery, export corridor		Hydrogen delivery, no export corridor	
	tstat	pvalue	tstat	pvalue	tstat	pvalue	tstat	pvalue
Costs, export corridor			6,66	0,00	0,27	0,79	0,13	0,89
costs, no export corridor					-4,75	0,00	-4,78	0,00
Hydrogen delivery, export corridor							-0,10	0,92
Hydrogen delivery, no export corridor								

Table I.23: Significance of the difference between the strategies in the random topology in regard to the hydrogen delivery

	Costs, export corridor		costs, no export corridor		Hydrogen delivery, export corridor		Hydrogen delivery, no export corridor	
	tstat	pvalue	tstat	pvalue	tstat	pvalue	tstat	pvalue
Costs, export corridor			18,50	0,00	8,90	0,00	16,70	0,00
costs, no export corridor					-6,60	0,00	-2,50	0,01
Hydrogen delivery, export corridor							4,41	0,00
Hydrogen delivery, no export corridor								

Table I.24: Significance of the difference between the strategies in the random topology in regard to the hydrogen export

J | VALIDATION

Extreme value testing has been performed on:

- the number of hydrogen source nodes in the system, which is put to 0
- the minimal utility for a pipe in order to change, which got a high value

The results of the two extreme values are compared to the normal situation with settings of the base case. They are all run with the same seed. The results are shown in table J.1. The results indicate that no hydrogen transition occurs when there are no hydrogen source nodes. This is a correct relation. In regard to a higher pipe utility, the option space for pipes to change gets more limited. This result is also found in the extreme value, as the amount of hydrogen delivered and exported are lower. Less transition has taken place, and therefore the costs are also lower.

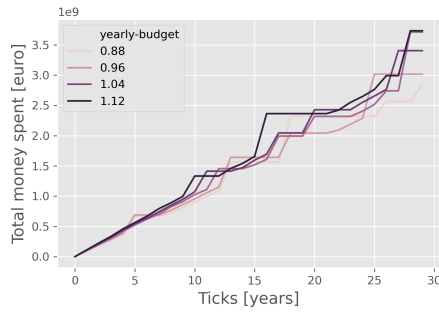
	Total costs	Hydrogen delivery	Hydrogen export
Base case	2,83	73,5	720
No hydrogen source nodes	0	0	0
High pipe utility (26)	0,27	24	432

Table J.1: Extreme value testing

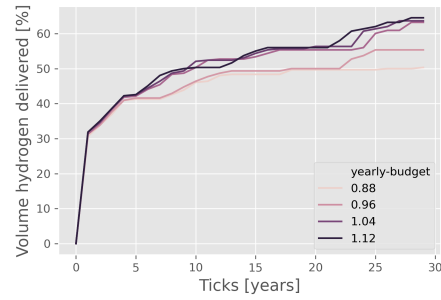
A sensitivity analysis on 4 parameters is performed. The standard setting is increased and decreased by 10 % with intermediate intervals. The parameters analysed are:

- the total budget, shown in figure J.1
- the costs for changing a natural gas pipe to a hydrogen pipe, shown in figure J.2
- the height of the utility when lower, natural gas is desired, and when not correctly attached, a tank needs to deliver natural gas, shown in figure J.3
- the height of the utility when higher, hydrogen is desired, and when not correctly attached, a tank needs to deliver hydrogen, shown in figure J.4

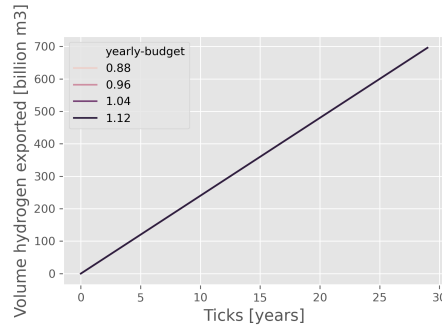
The results of the sensitivity analysis of the total budget show that the higher the available budget, the more this is also used and the higher the expenses. With more budget to spend, more hydrogen is delivered. There is no effect on the hydrogen delivery. This can be explained by the fact that in the base case, there is an export corridor, and from the first tick onward, the connection is established. For this reason, every year the full export demand



(a) Sensitivity analysis for the total budget on the total expenses



(b) Sensitivity analysis for the total budget on the hydrogen delivery



(c) Sensitivity analysis for the total budget on the hydrogen export

Figure J.1: Sensitivity analysis for the total budget

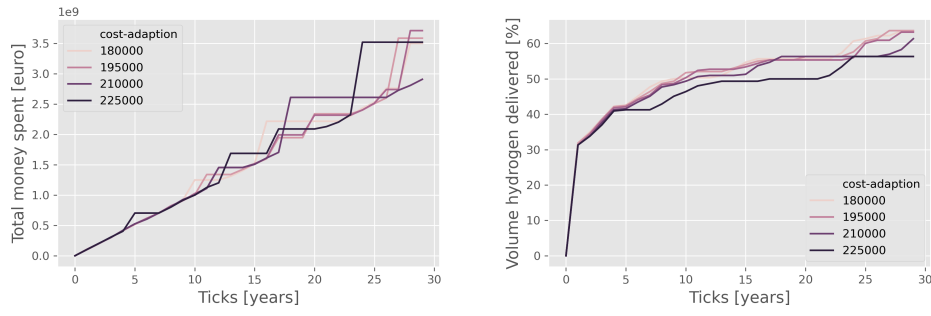
is met, and the total export therefore goes up linear.

The results of the sensitivity analysis of the costs for changing a pipe, show that higher adaption costs also lead to higher expenses. This is a logical effect. These higher adaption costs however lead to lower hydrogen delivery, as fewer changes can be made to the network. The same linear relation is found for the export. The explanation for this was already described above.

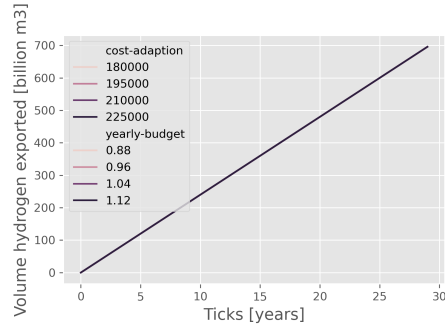
The results of the sensitivity analysis of the natural gas utility show that the lower this value, the quicker a tank needs to be allocated to deliver hydrogen to a wrongly connected node. This leads to additional costs. These higher costs then impact the hydrogen delivery, as more budget is spent on temporary connections, and less of the budget is allocated to transition the network.

The same, but then reversed, effect can be seen for the sensitivity of the hydrogen utility. When this utility is lowered, nodes need to be supplied by a tank earlier, and therefore more of the budget is allocated to temporary connections.

To conclude, the results of the extreme value testing and the sensitivity analysis show that the model reacts on changes in such a way that is logical.

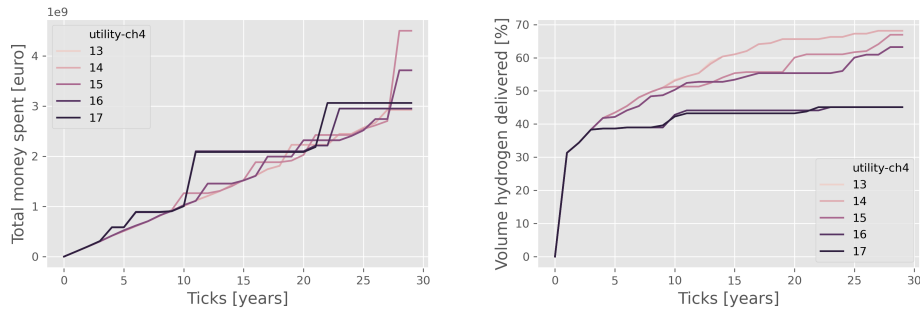


(a) Sensitivity analysis for the total budget on the total expenses (b) Sensitivity analysis for the total budget on the hydrogen delivery

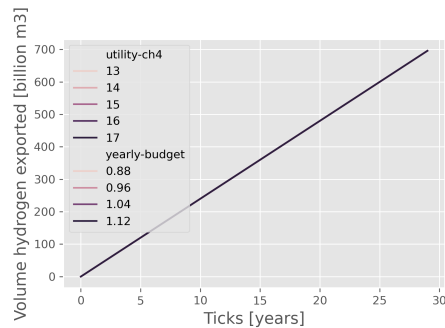


(c) Sensitivity analysis for the total budget on the hydrogen export

Figure J.2: Sensitivity analysis for the cost of adapting a pipe



(a) Sensitivity analysis for the total budget on the total expenses (b) Sensitivity analysis for the total budget on the hydrogen delivery



(c) Sensitivity analysis for the total budget on the hydrogen export

Figure J.3: Sensitivity analysis for the minimal natural gas utility

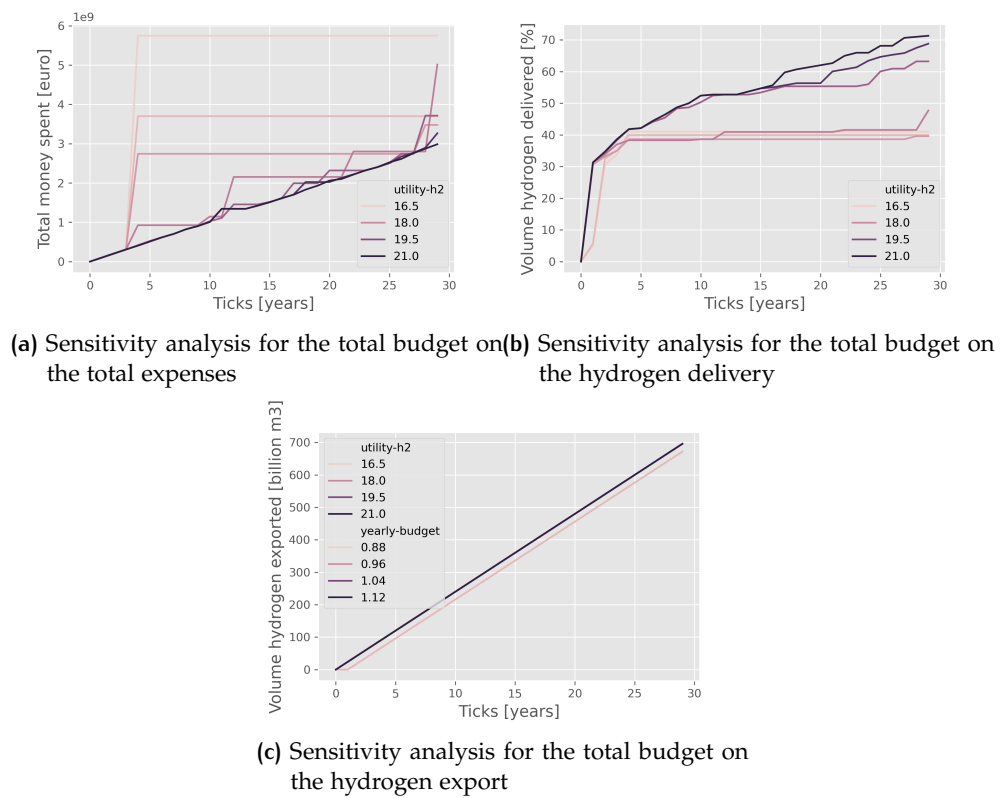


Figure J.4: Sensitivity analysis for the minimal hydrogen utility

K | PRACTICAL EXAMPLE FOR THE DUTCH SITUATION

In the Netherlands, there is a unique situation where two different qualities of natural gas are used, low-calorific gas from the Groningen field, referred to as L-gas or G-gas, and high-calorific gas, H-gas. Both these gas qualities have their own infrastructure. In this section, a calculation is made of the effect when one of these two infrastructures is changed to hydrogen, while the other network maintains to transport natural gas.

The L-gas is mainly used in the commercial markets and the built environment and is delivered to the consumers by the distribution network. A portion of the L-gas is also exported to Belgium, Germany and France. The H-gas is mainly used in industrial processes, to generate electricity and is also exported to neighbouring countries where it only comes through the Netherlands as a transit gas ([Ministerie van Economische Zaken, 2017](#)). The Dutch plans to reduce the production of the Groningen field have resulted in the reduction of export of L-gas. By 2030 the export of L-gas will be stopped completely. The export of H-gas will remain.

The two different gasses are transported separately in two different infrastructures, as can be seen in figure 4.1. With two separate gas infrastructures available in the Netherlands, an opportunity arises where one of the two infrastructures can be adapted and made ready for the transport of hydrogen. At the same time, the other stays intact to keep transporting natural gas. This concept has not been elaborated on in the literature or more practical reports. A quick estimation of the network concerning the required transition is made using the same input parameters that are used in the agent-based model. The comparison of the results of the models and will make it possible to draw more specific recommendations for the adaption of the Dutch gas infrastructure in specific.

K.1 CALCULATION OF THE TRANSITION

The Dutch transmission network has a length of 5330km, and the distribution network comprises of 5926 km pipes. The first assumption made is that half of the transmission grid transport H-gas and half transports L-gas so that $5330 * 0,5 = 2665\text{km}$ of transmission grid needs to be altered if we would change one of the two to hydrogen. When considering the distribution grid, only a part of the built environment will remain to be attached to the gas grid, and the majority will use an alternative energy source. The numbers in table 4.1 indicate that the built environment consumers 10,5 bil-

lion m³ natural gas, and when switched to hydrogen, the demand will be 9 billion m³. Given the fact that the energy content of natural gas is three times higher than the that of hydrogen, 28,5% of the supplied energy by natural gas will now be supplied by hydrogen.

The second assumption is that the mobility sector and other consumers attached to the distribution grid can benefit from the pipelines that are laid out to distribute hydrogen to the built environment. With this assumption made, 28,5% of the distribution grid needs to be alerted. This accounts for $5926 * 0,285 = 1689$ km.

The total length of pipes that therefore needs to be adapted in such a way that it can transport hydrogen is $2665 + 1689 = 4354$ km.

Concerning the costs, the costs for a new hydrogen pipeline are €2.000.000 per km. The explanation can be found in appendix B. Specifics on the cost of alteration of a natural gas grid to a hydrogen grid are not made specific. However, various sources implied that they are significantly lower than the construction of a whole new infrastructure. (Stedin and Kiwa, 2019) The costs are likely to be in the magnitude of hundreds of euros instead of thousands of euros (TNO) and presumably, it will be in the order of 5% to 10% of the costs of constructing a new infrastructure van Wijk and Hellinga (2018).

The total costs for the alteration of the part of the transmission and distribution grid account for €870.800.000.

As the network for the L-gas and the H-gas run parallel in most cases, as shown in figure 4.1, industrial clusters and electricity plant that are currently connected to the H-grid can easily connect to the new hydrogen grid. This transition can happen when the industrial cluster or electricity plant has made its investments in the combustion of the new gas type. The advantage of the double network with both hydrogen and natural gas is that both gasses are available, in comparison to the situation with a single network, all consumers are always connected to the network they need. In regard to the connectedness over time, no estimation of the development of connections and volumes can be given with this quick calculation.

The switching of the distribution grid does not have this same possibility as this only transports L-gas. As the current application of natural gas in the mobility sector is not significant, the main focus should be the built environment where natural gas is still widely applied. A solution is that parts of the distribution network should be isolated where the region can be transferred to use an alternative energy source (Ministerie van Economische Zaken, 2017). In this region, the not needed natural gas pipelines can be dismantled, and the gas pipelines that need to deliver hydrogen can be changed.

K.2 COMPARISON TO THE RESULTS IN THE AGENT-BASED MODEL

In the agent-based model, the aspect of the double grid is not included, and the transition network only represents the low-calorific gas network. The results indicate that this network is not very susceptible to lock-ins. This is already a positive finding. The double network even improves the Dutch situation, as the customers of the high-calorific gas always have both gases available. With this, the transition does not need to be pushed by the demand side. The drawback from this though is that the incentive for the customers to switch fuel type is not based on the available gas and the incentive should therefore be triggered elsewhere.

In conclusion, the double laid network in the Netherlands is an advantage for the transition; however challenges in the social subsystem remain.

