Design Space for Heat Network Systems:

Learning from the Gas, Electricity, Water and Wastewater Network Systems

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Design Space for Heat Network Systems:

Learning from the Electricity, Gas, Water and Wastewater Network Systems

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Preface

Dear Reader,

This thesis marks the completion of my academic pursuits. In this research I attempt to bring in the theories, concepts, methods and tools that I came across as a student at the TPM faculty of TU Delft. This research is a culmination of the learnings and its application in a real world problem scenario.

The two years as a student have been amongst the most memorable for me. There has rarely been a day when I haven't been excited about (lunch) lectures, projects and thesis. As a student studying Complex Systems Engineering, I realized that one develops a critical perspective and starts thinking in 'systems'. This learning sometimes helped but sometimes lead to a situation where I had to force myself to stop gong in further details. All done and dusted, I find myself happy at the end of this thesis research. However, it was by no means an individual affair. I was supported continuously across the thesis journey by several people.

Firstly, I'd like to thank my graduation committee at Technology Policy and Management faculty of TU Delft. Thank you to Prof. Rob Stikkelman and Prof. Aad Correljé who were always available to answer my questions and prod me in the right direction. Your feedback was valuable and helped me improve every time. I'd want to thank Prof. Rob Stikkelman in particular since your guidance has been an enormous help to me. I appreciate you taking out time after long week and sitting to guide me away from including everything in the world in the scope of the research. I'd like to thank Ir. Sjors Hijgenaar for providing me an opportunity to work with CGI on this thesis. I recall our weekly meetings a way for me to discuss my challenges and plans ahead. Thank you for your support throughout the thesis research.

Secondly, I'd like to thank my parents without whom I would have not been here. Their support and confidence in me kept me going every day. Thank you mom and dad! Also, big thanks to Daph, Rudri, Abhinay and Kanika for being there and trusting me in my decisions.

In the end, I thank all the friends, faculty and staff members who helped me in my journey to seek knowledge. I wish you, the reader, enjoy reading this thesis as much as I enjoyed my time studying for and writing it.

Abhinav Sharma

August 2019, Delft

Executive Summary

The changes in the global landscape of climate change and the regional development of earthquakes in the Groningen area has pushed Dutch government to transition away from natural gas in the future. However, natural gas has been a major source for heating in the Netherlands. As a move away from the natural gas based heating, the Dutch government identified district heating networks as most economical alternative to the natural gas. However, the future plans for the district heating sector have faced challenge on the question of the design of heat market and management of factors such as ownership, network access, tariffs and pricing.

The Design Space for Heat Network

The design space space is basically defined as a set of design variables that decide technical, economic and institutional aspects of a market. The choices made within this design space results in emergence of different types of market models. This thesis research focuses on the formulation of a design space for the heat network. The overarching question in this research is: *What technical, economic and institutional characteristics of network systems define the design space of a heat market?*

Learning from other network systems

The heating sector is basically a heat network system consisting of production, transportation and distribution through multiple systems operated my multiple actors. This draws similarity to the electricity, gas and water supply network systems which also comprise of similar sub-systems. This thesis draws learning from the existing networks for the design space of the heat network.

The approach taken for the research is conducting literature review, IDEF modelling and expert interviews. The IDEF model provides a functional understanding of the network systems in the research (Figure I).

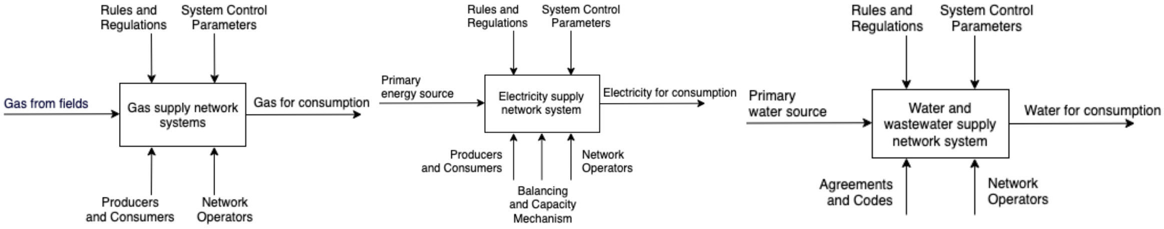

Figure I: IDEF0 context level diagram for gas, electricity, water and wastewater network system

The results of comparing the similarities and dissimilarities between the networks presented the following as network characteristics: Bidirectionality of flow, flow control, speed of flow, transportation losses, seasonality of demand, security of supply, storage, barriers to entry, geographic endowment, commodity differentiation and network criticality.

The learnings from the network systems were used and applied to identify the design variable for the heat network system. The characteristics such the regional nature of demand, speed of flow and geographic endowment excluded some of the design variables in the research. In the end seven design variables were identified for the heat network. These are as following: Degree of market opening, integrated versus decentralized markets, public versus private ownership, network unbundling, network regulation and tariff, integration with existing network and wholesale and end user pricing (Table I).

These variables along with their options form the design space for the heat network systems. The design space provides possible choices of heat markets by selecting a combination of design variables. The emergence of the heat markets from this design space is limited by the interdependence amongst the variables and policy goals, path dependence of the region.

Table I: Summarize design space for the heat network systems.

#	Design variable	Design variable options
1	Degree of market opening	Wheeling
		Single buyer model
		Wholesale competition
		Retail competition
2	Integrated versus decentralized market	Integrated market
		Decentralized market
3	Public versus private ownership	Public ownership
		Private ownership
		Public – Private ownership
4	Network unbundling	Separate accounting
		Organizational separation
		Judicial separation
5	Network regulation and Tariff	Negotiated third part access
		Regulated third party access
6	Integration with existing networks	Integrated network
		Non- integrated network
7	Wholesale and end user pricing	Max price for consumer
		Revenue capping for stakeholders

The thesis concludes that the design space of the heat network can be designed by drawing from the technical, economic and institutional characteristics of other network infrastructures. Further it presents recommendations based on the pros and cons of various design options in the design space.

1. **Decentralized development of heat networks.** The choice of market opening for the heat sector in tandem with region based zoning can provide a design choice for regional heat markets with differentiated prices.
2. **Distributed ownership of heat networks.** In case of an integrated network plans such as the '*heat roundabout' (Warmterotende)*, and '*pipeline through the middle*' (*Leiding door het Midden*) the ownership can be distributed as public, private and public-private across the network.
3. **Compatibility with water and wastewater networks.** The comparability between the network system of heat and water and wastewater supply network throws open a possibility of integration of the two networks.
4. **Focus on information management.** The flow of information is an important part of the heat network systems. Technology firms can invest in research on the technical solutions for collection of data from the users (via heat meters), profile generation, demand forecasting would be required.
5. **Focus on asset management.** The increase in participation of stakeholders in the heat market creates possibilities of assets and customers changing ownership amongst wholesaler and retail supplier of heat in the future markets. Technology firms with their experience in technology such as blockchain and smart contracts, can develop a business case in these emerging heat markets.
6. **Harnessing diverse knowledge pool.** The comparability between the different network systems presents the insight that different sectoral teams within firms located globally can collaborate and work together.
7. **Collaborations with technology companies.** The technical expertise in the development of solutions for the heat markets can be conceived inhouse. Firms can also collaborate with other engineering companies. An alternative way is to look at acquiring small companies and star-ups that work on the state of the art heat network technology.

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1 Introduction

This chapter introduces the research topic of design space for heat networks. In Section 1.1 the problem of heat sector is presented. In Section 1.2 and Section 1.3 the present situation and future plans for heating sector in the Netherlands are discussed. In Section 1.4 the research gap is identified based on the problem in the heat sector and current research in the domain. The chapter is summarized in the Section 1.5.

1.1 The heat problem

The heating sector in the Netherlands faces challenge of meeting its long term climate goals with cost effective solution. In December 2016, the Ministry of Economic Affairs published an energy policy framework (*Energieagenda*) setting targets for emission cuts. The Energieagenda plans to drastically reduce the usage of natural gas in all sectors in order to reduce the emissions by 95% by 2050 (Ministry of Economic Affairs, 2016). This is a complex situation for the heating sector as natural gas has been a primary source of residential space heating (van ‘t Hof, 2015). The data from 2014 show that natural gas accounts for 70% of heating in the Netherlands (refer Figure 1). Rest 30% is the shared by electricity (20%), district heating networks and solid fuels (8%) (Kreijkes, 2017).

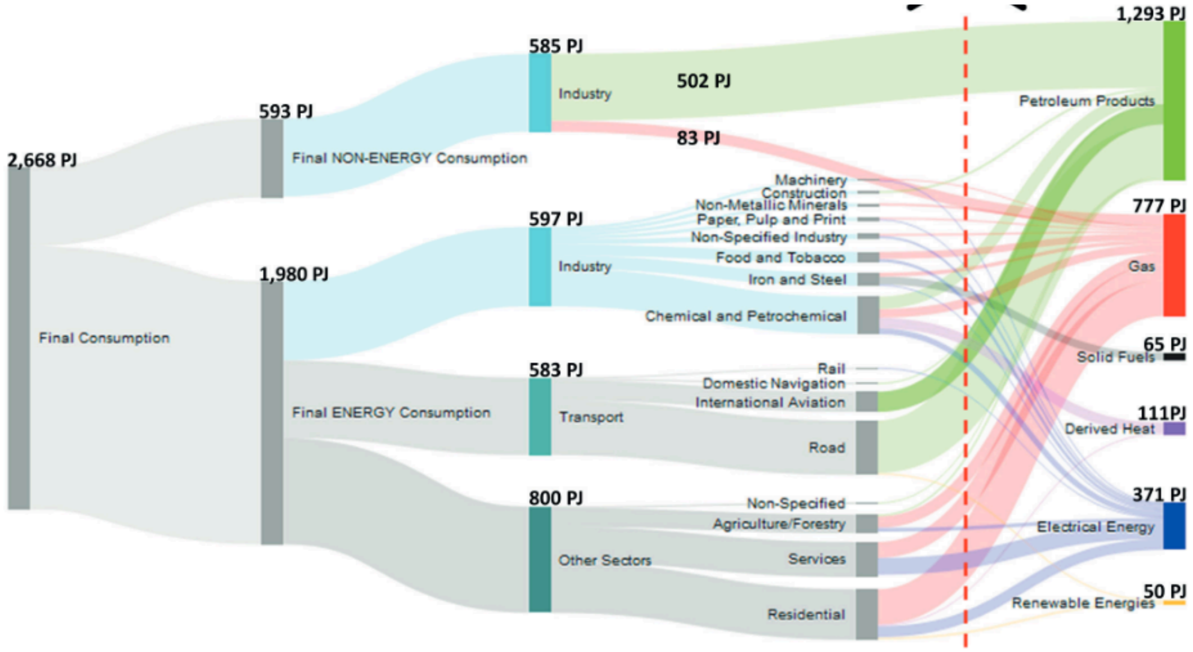

Figure 1: A Sankey diagram of the Dutch energy consumption and supply in 2014. On the left side the final consumption is illustrated which is being met by the production (including imports) on the right side of the diagram. Adapted from Kreijkes (2017).

It is worth mentioning that earthquakes in Groningen region of the Netherlands have been a major factor for the energy sector to move away from natural gas. The natural gas extraction has been attributed to an increasing number of mild earthquakes (Mulder et al., 2018). Thus, the climate change targets and earthquakes are the primary reasons for the Dutch government to transition away from natural gas for the residential and horticultural sectors by 2030 (Van 't Hof, 2018). A move away from the natural gas therefore creates a problem for designing the new heating sector in the Netherlands. This is the broad domain of research for this thesis as we look into the Dutch heat sector. But first, it is important to see what is the present situation. The next section takes a look at the current heating and district heating scenario in the Netherlands.

1.2 The present: Dutch heating scenario

The move away from the natural gas based heating allows alternatives such as electricity based heat pumps, solid fuel fired boilers and district heating to substitute the gas heating market. The Dutch government identified heat networks as most economical alternative to the natural gas (Stichting Platform Geothermie, 2018a). Therefore, we focus on the status of existing heating networks in the Netherlands.

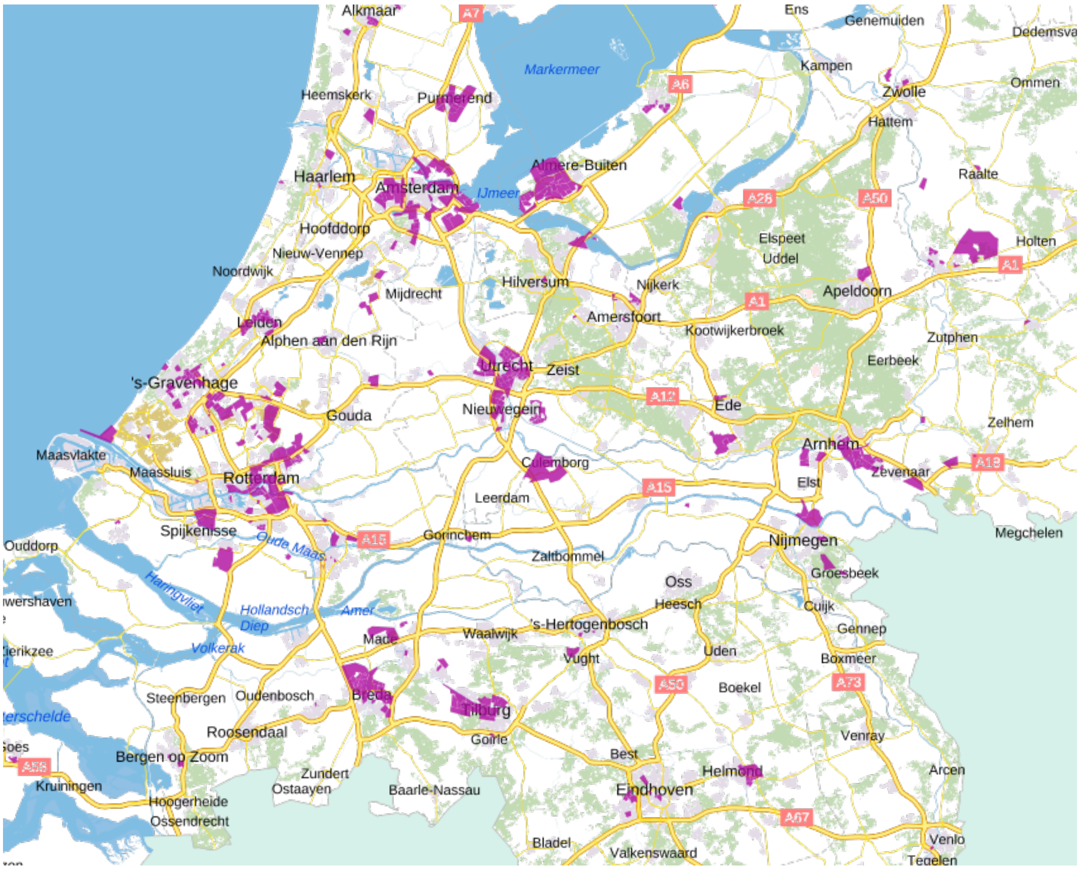

Figure 2: District heating connected regions in the Netherlands (highlighted in Pink color)[1]

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[1] Source: www.warmteatlas.nl.

At present, heat is supplied to over 300 small scale girds and 227,000 customers in the Netherlands[1] by thirteen large scale heat grids. The major suppliers to these grids are Essent, Eneco and Nuon. In addition to the large scale grids, there are more than 6,600 small scale grids that are owned and operated by housing corporations, owner associations, and individuals, and these supply heat to 336,000 homes. However, these district heating connected houses is very low (see Figure 2) and accounts only for 4.4% of the total dwellings.

At present the price for heat is determined by the 'heat law' (*warmtewet 1.0*) set by the Autoritiet Consument and Markt (ACM). The ACM is the Dutch regulatory body that sets the price of heat based on the 'not more than other' (NDMA) principle for consumers and oversees the bilateral contracts between the heat producers and distributors.

1.3 The future: A difficult road ahead

Despite the low number of consumers presently connected to the heat networks the PBL Netherlands Environmental Assessment Agency forecasts district heating providing for 90% of the heating requirements (Van 't Hof, 2018). Looking at the available sources of energy supplying heat to the district heating networks geothermal energy comes out as a strong alternative. It is expected to provide over 200 PJ of heat energy demand by 2050, which covers almost half of the urban heat demand. Other future source include connecting different regional heat networks together. A heat roundabout ('*warmterotende'*) is planned to deliver waste heat from the port of Rotterdam to over 350,000 households and 1000 acres of greenhouses (Stichting Platform Geothermie, 2018b).

These future plans for the district heating sector have faced challenges of ownership of the network, access to network, tariffs and pricing. For example, the at present the the heat is priced at parity with gas with phasing out of gas the problem of pricing for heat arises and there is no clear alternative available yet (Klimaat, 2018).

The challenges ahead for the district heating sector are manifold. Starting from the technical issues of drilling technology for Geothermal energy and lack of subsurface data to construction of pipeline networks. The institutional dilemma of setting up either an open and competitive or vertically integrated and regulated market remains. At last the question of access, tariff design and how much a customer be charged for heat remain and make the future a difficult road ahead.

It is not a surprise that the challenges in the heating sector have captured the interest of professionals and researchers. Several research have been conducted in each of the areas mentioned previously. In the next section we take a brief look at the available research and identify the gap in the academic research scenario.

1.4 Research gap

As discussed previously, the heat network systems with multiple stakeholders and interconnections can be represented as infrastructure systems. In case of bringing in reforms in these network infrastructures both technology and institutional aspects need to be aligned (Künneke Rolf et al., 2008). There are researches in the domain of heat network system which attempt to look at the technical, institutional and economic aspects.

On the technology side, Lastiri (2013) researched the technical configurations for the district heating networks for increasing the efficiency of the network. Higher efficiency of the district heating network is seen as a potential for it to expand into large thermal networks (Rezaie & Rosen, 2012). Apart for heating purposes, district heating is also seen to provide flexibility through heat storage in electric boilers for renewable energy production (Erik et al., 2003).

In terms of economic aspects of the district heating networks, Guichard (2018) studied the impact of pricing mechanism and transmission losses on the performance of the competitive market and concluding the effect were divergent. Van der Ende (2018) compared a local market driven approach versus a regional plan driven approach for design of a low temperature heating system in south Holland using models and simulations. Another modelling based research was conducted by Bijvoet (2017) exploring the competitive behaviour of the actors in an open district heating network in the Netherlands. Söderholm (2011) presented that owing to the localized scope of the heat networks a negotiated third party access system would be efficient than a competitive market with regulated third party access.

It is interesting to note that heating sector is basically a heat network system consisting of production, transportation and distribution through multiple systems operated my multiple actors. This allowed many researches in the domain of electricity, gas and water supply to be extended to the heating sector. Pan (2016) studied electricity and heat network as an integrated system and modelled the energy flow in such a system understanding the impact of one system on the other.

Through a brief literature review we see that broadly, the heat network systems are studied as a standalone network systems compared to with other heat systems or as an integrated system with electricity. This leaves a space where there is a lack of research into comparison of the heat network with other network infrastructures. And exploring the possibility of drawing from the technical, institutional and economic characteristics of existing network infrastructures to understand the heat sector.

1.5 Research questions

In light of the problem discussed about the transition to a heating sector without gas and limited research into comparability of different network infrastructures vis-à-vis heat network, the research question is framed as follows:

What technical, economic and institutional characteristics of network systems define the design space of a heat market?

The main research question seeks to draw from the technical, economic and institutional characteristics of electricity, gas and water and wastewater network systems to define a design space for the heat market. These network infrastructures may differ in terms of their physical characteristics and complex interactions in their network. Therefore, to answer the main research question following sub-research questions are identified:

i. What are the similarities and differences in terms of technical, institutional and economical characteristic of heat network with electricity, gas and water and wastewater networks?
ii. What are the design variables that are relevant to the heat network systems?
iii. How is the design space defined for the heat network systems?

The first research question provides an insight if there are indeed similarities and differences between the heat and other network infrastructures. If yes, then what are those and how? The answer to this question leads to the second research question where we use the identified similarities and differences as constraints to identify the design variables applicable for the heat market. The options for the heat market variables are therefore imported from the network infrastructure they resemble. In the last research sub question we compile all the design variables together into a design space for the heat network.

In conclusion, this research would provide a broad design space for the heat network building on the relevant learnings from the existing network infrastructures of electricity, gas, and water and wastewater network systems.

1.6 Summary

This chapter introduced the heat problem in the Netherlands due to the present trends and future developments at the global and local scale respectively. It covered a brief literature review to present the limited work done in comparative study done of heat network with other network systems. Building on this, the research problem on identification of design space for heat network was formulated and defined in multiple sub research questions.

2 Methodology

This chapter focuses on the methodology for the research to be conducted in this thesis. The Section 2.1 looks at the network infrastructure as a complex socio-technical system. It then outlines a complex systems engineering approach and the theory of systems thinking to understand the system, sub-system and their interactions. The section also presents a schema to create a design space for heat network systems based on the systems thinking method. In Section 2.2 the research method is detailed by defining modeling and data analysis techniques to create a systems view of the network infrastructure for further analysis. In Section 2.3 we summarize the research methodology and research flow. We end the chapter in Section 2.4 by defining the structure of the thesis based on the research problem, methodology and flow.

2.1 Systems view of network infrastructure

In this research we plan to compare the network of heat, electricity, gas, water and wastewater with each other and draw relevant learnings. For this, we first take these network infrastructures as different 'systems'. A 'system' is defined as a purposeful whole consisting of multiple interacting parts (Roedler, Forsberg, & Hamelin, 2017). A systems view is able to provide a perspective to explore network infrastructures as complex systems by first looking at the 'parts' in isolation as sub-systems and in then in combination as 'interactions between the parts'. This approach helps in understanding the functionality of different network infrastructures and provide a generic view of the underlying complex systems for further analysis.

2.1.1 Network infrastructure as complex system

Network infrastructures are defined as socio-technical systems designed for transport of people and goods (Herder, Bouwmans, Dijkema, Stikkelman, & Weijnen, 2008). Some examples of these systems are the electricity network, gas network, telecommunication network, water and wastewater networks. Over time the growth of innovative and alternative technologies led to a change in the political geography of supply and demand along with physical supply chains resulting in emergence of complexity in these systems (McDermott, Nadolski, Sheppard, & Stulberg, 2015).

Due to the complexity, Herder (2008) adds that behavior of these infrastructures cannot be understood by considering only the physical or the social network.. The two networks are interlinked and associated in multiple ways and the quality and reliability of service are dependent on performance of the two as an integrated system. The combination of these two systems that are complex in themselves and their interactions result in emergence of a new domain of complexity of the integrated system. This complex interaction of physical and social (actors) network is shown in Figure 3.

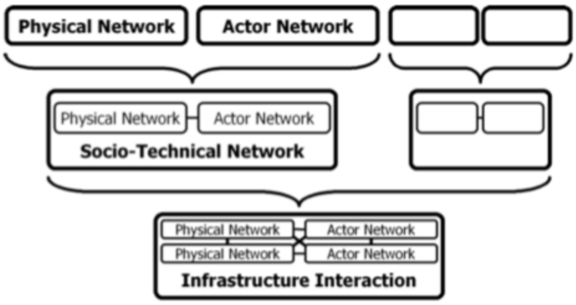

Figure 3: Domains of complexity in network infrastructure. Adapted from Herder (2008).

In this research, the network infrastructures are identified as complex systems and a systems engineering approach is adopted to explore the design space of heat network systems. A systems engineering approach takes into consideration the multiple parts of the system as a whole and importance of relation of the system elements with the system itself. The systems thinking occurs through discovery, learning and dialogue that lead to sensing, modeling and better understanding of the real world (problems) (Roedler et al., 2017). The complex systems engineering approach minimizes the complexity of the network system by minimizing unknown consequences arising from interactions of sub components (Weijnen & Bouwmans, 2006).

2.1.2 Systems thinking in network infrastructure

The network infrastructures under the scope of this research include the electricity network, gas network, water supply and wastewater network, and the heat energy network. Broadly, we see that all these networks deliver critical services from two geographically distanced locations to meet the demand. Therefore, collectively, we can abstract these as a high level system with an input, output and process of 'delivering energy or a resource'.

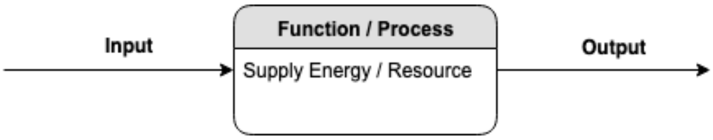

Figure 4: Network infrastructure abstracted as a system.

At a high level the different network look and function in a same manner. This simplified systems view (in Figure 4) is able to broadly define the previously mentioned network infrastructures. For example, the electricity network can be explained as a network that takes in energy from the resources and distributes power to the consumers at different locations. Similarly, the water supply network abstracts clean water and supplies it to various customers.

However, going at sub-system level in the network infrastructures, we see the variations between different network structures start to emerge. The difference exists basically due to the physical characteristics of the commodity and transportation network. This results in variation in technical sub systems and their interactions. Künneke et al. (2010) identifies that different infrastructures have different critical transactions based on the different alignment of technical functions and institutional functions.

Taking a systems thinking perspective a comparison of the networks provides opportunity to play around with various network components to create new networks. Langfred (2010) draws the analogy of the gas network systems as a 'Lego' block due to the features such as a) network being made up of different components, b) ability of components to be combined in different ways and c) various possibilities of combination having 'path dependencies' on series of sequential decisions of components being added.

Using systems thinking this analogy can be extended to other existing network infrastructures whose physical characteristics, components, connections and topologies are known and corresponding driving principles and regulations exist. One can see this as a scenario where *a) different boxes of Lego structures are opened together and b) a new Lego structure is designed based on selecting components that is a best fit from any of the other boxes.* In Figure 5 below, it is shown how a design space for the Heat network system may be realized by identifying sub-systems and relations similar to other existing network infrastructure.

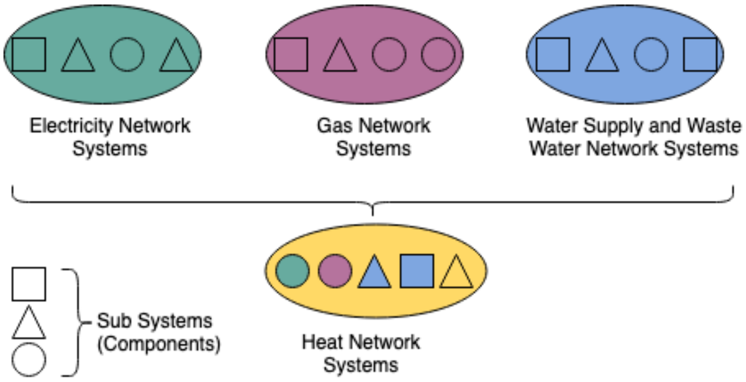

Figure 5: Systems thinking and a 'Lego' approach for designing a heat network systems. The Square, Triangle and Circle represent different types of technical, institutional and process artefacts in different types of systems (differentiated by different colors).

The thesis research had two options for selecting the possible network systems to drawing learnings from. First option was to only consider the utility markets in the Netherlands. This would make sense as the scope of the heat market is also kept in the Netherlands. The comparison drawn in this case would be more relevant and contextual. The second option was to look internationally for the most developed markets irrespective of the region.

In this case, the benefit will be that we draw learnings from the network systems from the most developed markets and get better insights as the markets would have evolved from different stages of liberalization. In the end, it was decided to go ahead with the second option and the developed markets were chosen across the region. These are as shown in Table 1:

Table 1: Selected sector per network systems for thesis research

Network system	Selected sector
Electricity	Dutch electricity sector
Gas	Dutch gas sector
Water and wastewater	UK water and wastewater sector
Heat	Dutch heating sector

Here, we take a quick look at the Dutch water and wastewater market scenario. In the Netherlands at present there are 10 drinking water companies serving over 8 million connections (Geudens & Grootveld, 2017). Apart from these Water transportmaatschappij Rijn Kennemerland (WRK) and Waterwinningsbedrijf Brabantse Biesbosch (WBB) provide recycled water to the industries. Multiple water production and distribution companies are active in wastewater treatment. Legally all the water companies are public limited with municipalities as shareholders (Geudens & Grootveld, 2017).

This approach of designing a system by drawing from other network infrastructures has been used historically in other novel network infrastructures before. The gas network unbundling and liberalization in the Netherlands followed the electricity sector. Acts such as Transition Act for Electricity Production, Mining Act (*Mijnbowwet*) and the European Gas Directives were preceded by similar acts leading to liberalization of the electricity sector.

The challenge then in this methodology of using a systems thinking approach is to use a common language that can abstract sub-systems relationships accurately, without going in high level of details or being so abstract that it loses critical information. In the next section we identify the methods and models used to tackle this research challenge.

2.2 Design Research Methodology

The task of defining a design space for a heat network system can be seen a design research problem. In a novel network infrastructure design the research must understand as well as improve the existing design. Blessing & Chakrabarty (2009) state that design research has two objectives: creation and validation of theories and models that deal with the phenomenon of design, and second, development and validation of support based on these artefacts to improve design. Thus, design research is made more effective and efficient with the help of DRM.

In case of this research, we can understand the use of DRM as a part of process as shown in Figure 6 as: a) the design to be ‘identified’ as the design space (or framework) for heat energy network systems, b) design research to be a modeling technique and approach used for the design, and c) design research methodology as an iterative process of revisiting the design space and model to improve the design during the research.

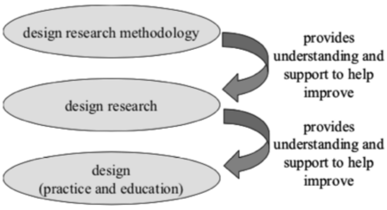

Figure 6: Relation between design, design research and design research methodology.

With the DRM approach in this thesis we use literature review, structured interviews, and IDEF0 modelling to conduct the design research. These are explained in detail in the following sections.

2.3 Functional Modeling: IDEF0

In 1970's, the U.S. Integrated Computer Aided Manufacturing (ICAM) unit sought to increase the productivity through better analysis and communication technique. The IDEF (Integrated DEFinition language) technique thus developed and a variation of the technique that focused on the 'functional model' of a system with inputs, outputs, activities and control mechanisms was defined as the IDEF0 (FIPS PUBS, 1981). IDEF0 is a graphical modelling language with semantics and syntax.

The main elements of the IDEF0 include: Inputs depicted by arrows flowing into the left hand side of the activity box, outputs depicted by arrows flowing out of the right hand side of the activity box, with the activity (or process) being represented by the box themselves. The arrows flowing into the top portion of the box depict controls or constraints on the activities, and the mechanisms that carry out the activity are represented by arrows flowing out from the bottom of the activity box (refer Figure 7).

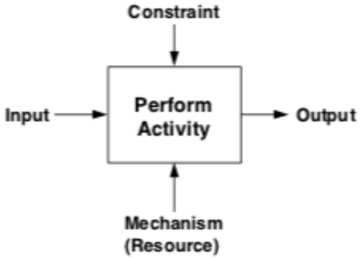

Figure 7: A top-level IDEF diagram.

The transition from systems thinking to a systems modelling improves the qualitative and quantitative understanding of the problem. Tools such as the Unified Modeling Language provide various means for simplified representation, an example is the activity diagram which can describe a system in a standardized structure for easy understanding (Ríos, Barton, & Pérez, 2012). In this thesis research we employ the IDEF (Integrated Definition) modeling language for the modelling of the network infrastructures.

The advantage of IDEF0 modeling language is that it provides a common language to abstract the network infrastructure of electricity, gas, water supply and waste water, and heat energy. Once we are able to break down these into sub systems and the relations we can draw relevant similarities and dissimilarities between each of them to design a heat energy network system.

2.4 Literature review

A literature review is conducted in two cases, first, in case of mature topic with accumulated body of research, a thorough literature review can result in the development of a conceptual model that would help amalgamate and build up on existing research. Second, in case of emerging topics a literature review based on theoretical foundation lead to new contributions (Webster & Watson, 2002). In case of this research, literature review of existing network systems on the concepts of technology, institutions and regulations and economic was undertaken. The review provided a fundamental knowledge of the technical, economic and institutional aspects of the network systems for further analysis.

At an initial phase (that is problem identification and methodology selection) literature review helps in identifying the further steps of methodology such as modeling tools and structured interviews by providing specific information enabling development of accurate models and designing of discussion points for interview with the stakeholders and experts.

2.5 Interviews

Interviews are one of the formal requirement elicitation techniques to garner useful information. Faulconbridge (2018) goes on to describe interviews as a ‘one-to-one’ structured workshop and emphasizes on the need for preparation for both, the interviewer and interviewee. The (expert) interviews result in collection of subjective judgements with the possibility of error being in the methodology of collecting the data. Roedler (2017) highlights the importance of the interview methodology used to collect data to be thoroughly documented and defensible.

In this thesis research, the experts and stakeholders are selected by first reaching out to through the network of the thesis supervisors. Then a snowball technique is employed to reach out to sector specific experts and stakeholders for a holistic understanding of the network infrastructure. The interviews were conducted in two phases. In preliminary phase interviews were used to plug-in the knowledge gaps from the literature and to complete the systems model (IDEF0). In the second stage the interviews were used to discuss the results of research and get opinion of the experts. The Table 2 below indexes the interviewees and their sectoral area of expertise.

Table 2: List of interviewees with their sectoral details

Name	Designation	Sector	Remarks
Mr. Sanjay Ganeshan	High Voltage Engineer	Electricity network	Technical and economic insights into the electricity networks in the Netherlands.
Mr. Roelof Reineman	District Heating Expert, Eneco	Heat network	Technical and economic insights and expertise in the District Heating network in North Rotterdam and the Netherlands. Brings in the perspective of heat companies.
Mr. J.T Krouwel	Gas Network Specialist	Gasunie	Technical expertise in Gas networks
Mr. W.G. (Wil) Kovacs	Head of Pipeline office and Subsurface Management	Municipality of Rotterdam	Expert in subject of subsurface and pipeline layout in the Rotterdam region

2.6 Validation

The validation of the design space for the heat network systems which is developed in a qualitative inquiry is a critical activity. The term ‘validation’ is defined as the accuracy in representing participants realities of the social phenomenon (which in this case is the heat network infrastructures) and its credibility (Schwandt, 1997). Creswell (2000) identifies various validity procedures based on the paradigm assumptions and view point of the inquirer. In this research we validate the results through convergence of information from various sources to form a theme of study. This validation can be done through observations, interviews, document reviews and corroborating data analysis.

This thesis research validates the design space through expert interviews and review of the existing heat market. The experts for the interview are selected on the basis of their relevant industry and academic experience in the heat (and other) energy sectors. The markets selected are from Sweden and Denmark. These two markets were selected as they provided a different range of design variables that they comprised. The framework for heat energy markets are referred from the works of research scholars.

2.7 Flow and structure of thesis research

2.7.1 Flow of thesis research

The discussion on the methodology for the thesis research in this chapter can be summarized as an approach where the objective of ‘identifying a design space (for heat network)’ is accomplished by bringing in learnings[2] from existing (electricity, gas, and water and waste water) complex network infrastructures. The research flow diagram (Figure 8) shows flow of research along with intermediate and final deliverables.

The process of extraction of learnings from existing network infrastructures and their analysis is planned by first taking a 'complex systems view' of the networks from the theory of 'systems thinking'. Post that, a design research methodology is used that employs IDEF0 modeling language to draw a rich graphical representation of the networks for analysis. The use of literature review and structured interviews assist in re-aligning the network models for a more realistic representation. We see that this method would abstract a modular understanding of the existing infrastructure systems.

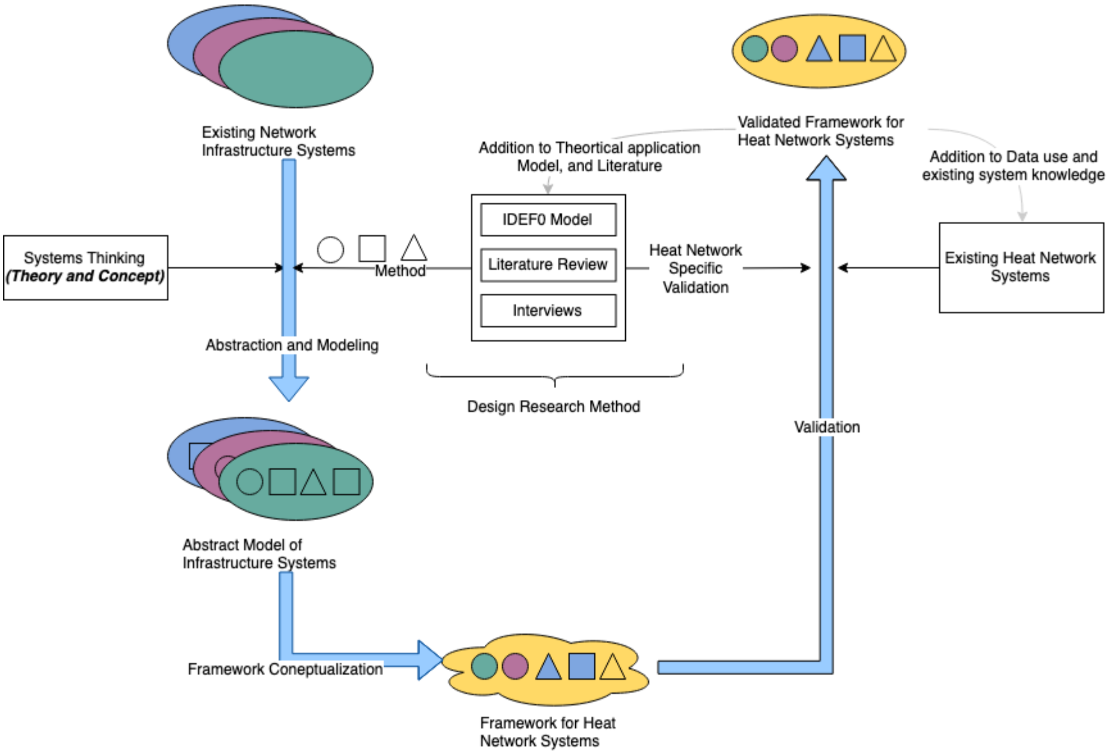

Figure 8: Flow of thesis research.

This step is described as resembling a play of components similar to the 'Legos' as mentioned previously. The deliverable from this part of research would be a framework which would draw from critical technical, institutional and economic aspects of a heat network systems.

Amongst, the framework for the heat network systems we also find addition to the theory of systems thinking by expanding it in the domain of new network infrastructure and coupling with IDEF0 modeling language. The steps in the research and deliverables are discussed in

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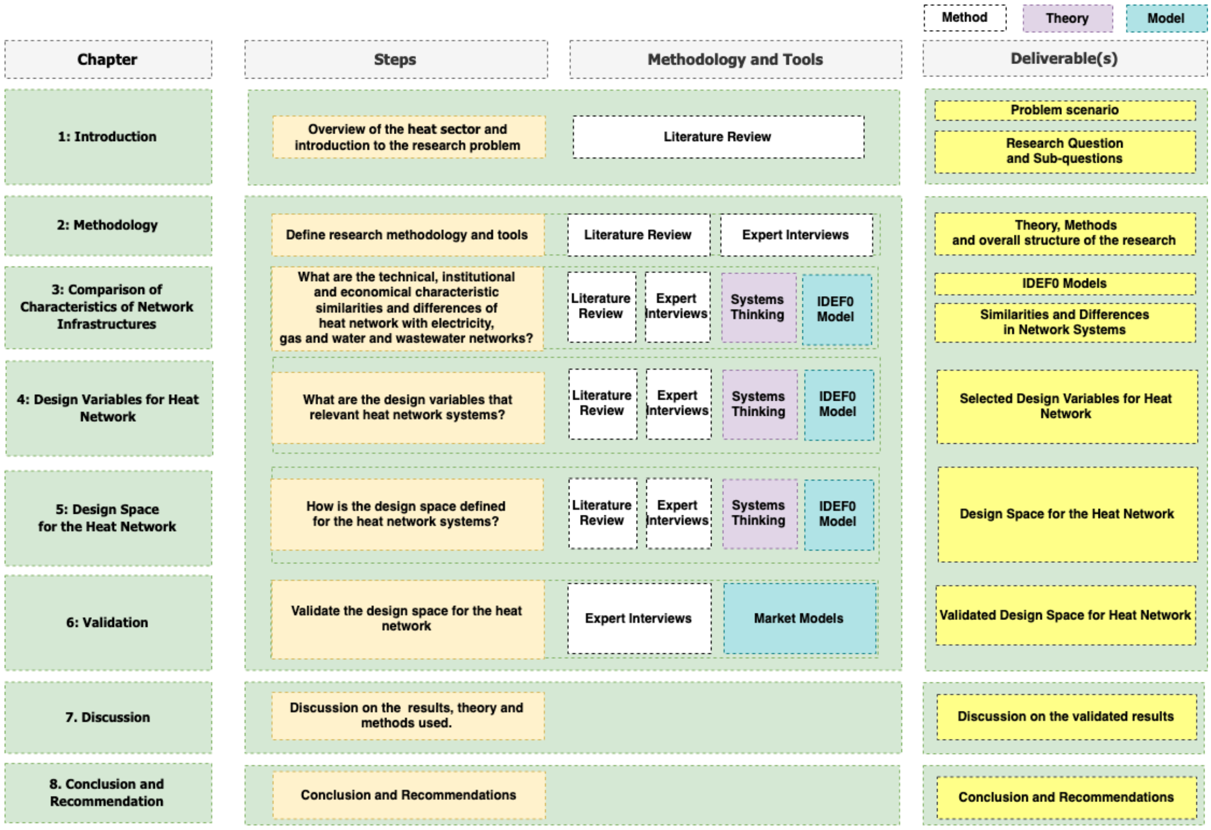
[2] The learnings are drawn from analytical comparison between network infrastructure of electricity, gas, water and wastewater network. The similarities and dissimilarities on technical, process, institutional, regulatory and economic level amongst the network are referred to as learnings (as they can provide valuable insights) for designing a new infrastructure.

detail in the next section where the structure of the thesis is discussed.

2.7.2 Structure of thesis research

The Chapter 1 and 2 set the context of the research by introducing the problem and research methodology respectively. The Chapter 3 focuses on the first sub-research question of identifying the technical, institutional and economical characteristic similarities and differences of heat, electricity, gas, and water network. In this chapter we use systems thinking theory and the review literature on the characteristics of network infrastructures to draw insights. Also using IDEF0 modeling language we design models of network systems for comparative analysis. The chapter is concluded by identifying the relevant factors for heat network that constrain the selection of design variables. In Chapter 4 we use the results from previous chapter and identify the relevant design variables for heat network. In Chapter 5, using the design variables the design space for the heat network systems is designed. Next, in Chapter 6 we validate the design space by examining its application to the existing heat markets and discussions with the industry experts. In Chapter 7 we discuss briefly the results and the methodology used for the research. We conclude in chapter 8 by revisiting the research questions and providing recommendations for the heat sector.



Method Theory Model

Chapter	Steps	Methodology and Tools	Deliverable(s)
1: Introduction	Overview of the heat sector and introduction to the research problem	Literature Review	Problem scenario Research Question and Sub-questions
2: Methodology	Define research methodology and tools	Literature Review Expert Interviews	Theory, Methods and overall structure of the research
3: Comparison of Characteristics of Network Infrastructures	What are the technical, institutional and economical characteristic similarities and differences of heat network with electricity, gas and water and wastewater networks?	Literature Review Expert Interviews Systems Thinking IDEF0 Model	IDEF0 Models Similarities and Differences in Network Systems
4: Design Variables for Heat Network	What are the design variables that relevant heat network systems?	Literature Review Expert Interviews Systems Thinking IDEF0 Model	Selected Design Variables for Heat Network
5: Design Space for the Heat Network	How is the design space defined for the heat network systems?	Literature Review Expert Interviews Systems Thinking IDEF0 Model	Design Space for the Heat Network
6: Validation	Validate the design space for the heat network	Expert Interviews Market Models	Validated Design Space for Heat Network
7. Discussion	Discussion on the results, theory and methods used.		Discussion on the validated results
8. Conclusion and Recommendation	Conclusion and Recommendations		Conclusion and Recommendations

Figure 9: Structure of thesis research.

3 Comparing Characteristics of Network Systems

In this chapter, we compare the characteristics of heat, gas, electricity, water supply and wastewater networks and draw similarities and differences between them. This is done by exploring the technical, economic and institutional characteristics of gas, electricity, water and wastewater networks in Section 3.1, Section 3.2, Section 3.3 and Section 3.4 respectively. These section also include the IDEF0 models of the different networks. In Section 3.5 an analysis is done of the characteristics and similarities and differences are summarized.

3.1 The Heat network systems

The heat network system has evolved over time in the Netherlands. The first known heat network in the Netherlands was laid down in 1923 in Utrecht. At the time coal based boilers were mostly used for heating houses. The oil crisis of 1970's triggered a peak in the development of heat networks as the need to save fuel lead to expansion of district heating networks (Osman, 2017). In 1960's, the discovery of the gas fields and its accessibility to municipalities made natural gas the main source of heating. By 2013, 4.4% of the households in the Netherlands were connected to the district heating networks. Natural gas remains as a preferred means of spatial heating serving more than 90% of the households[3] (Figure 10).

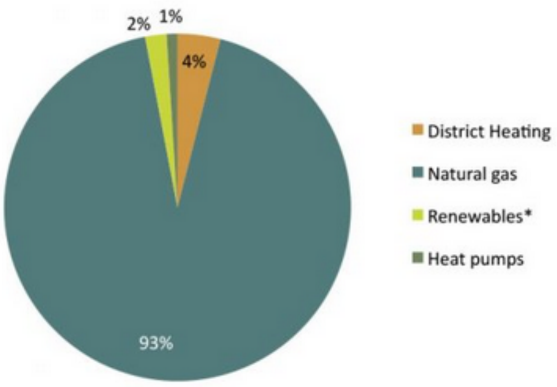


Figure 10: Different means of residential heating in 2013 in the Netherlands.

The heat demand in the Netherlands is mostly for the agriculture, industry and household consumption (refer Figure 1). These are heated through High temperature and low temperature heating networks. The high temperature heating networks serve the industry

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[3] Sourced from: https://www.euroheat.org/knowledge-hub/district-energy-netherlands/

while the lower temperature network provide heat to the agricultural households, agricultural greenhouses and utilities (Figure 11).

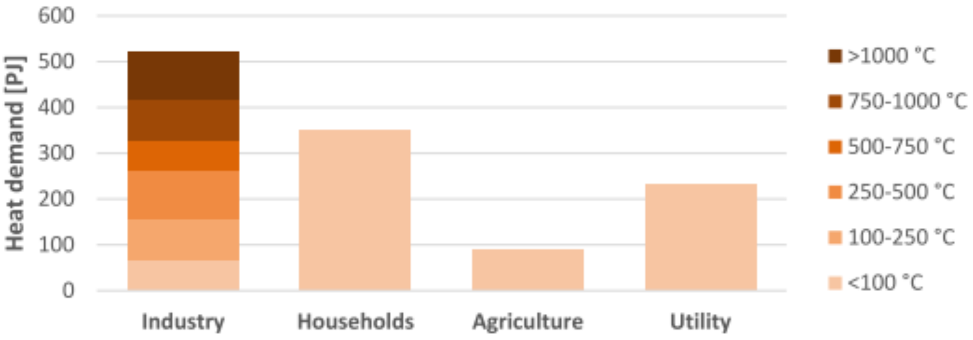

Figure 11: Sector wise heat demand and consumption. Adapted from (Oei, 2016).

With the global landscape push to r phasing out of natural gas[4] district heating is emerging as an alternative for heating. Molen (2018) identifies that for the transition (from gas based to district heating based heating) to meet the national targets the high temperature and low temperature district heating needs to cover more than half of the heating requirements

We now go deep to explore what comprises a heat network, institutions and regulations specific to the Netherlands heating sector in the next section.

3.1.1 Technical characteristics

Production. The main sources of heat production are combined heat generation plants (CHPs), geothermal energy, biomass, bio-fuels, natural gas, solar heat, industrial waste heat, solid waste incinerators and heat pumps (Etsap & Brief, 2013). The production of heat from the CHP plants requires water of specific quality[5] to prevent corrosion and coatings in the transporting pipelines. The heat exchangers transfer the heat from the central boiler and delivers it via the network to consumers. In the transportation network, the main cause of loss of heat is pipe friction that depends on the density and volume of the fluid flowing and length and diameter of the pipes (Groot, 2014). These characteristics impact the layout and the functioning of the technical systems.

Transportation. The produced heat is transported and distributed through insulated pipeline network carrying water as the heat transfer fluid. The hot water flows at a temperature ranging from 70 ºC to 130 ºC and return at a temperature of 35 ºC to 70 ºC. Ideally the input temperature for distribution network is 120 ºC and return temperature is 70 ºC in the heat network (Danfoss, 2019).

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[4] Source from: https://ec.europa.eu/energy/sites/ener/files/documents/01.b.02_mf31_presentation_nl-fuel_switch-vanthof.pdf

[5] Usually water in the pH range of 9-10, and hardness of 0.1 tH is used.

The heat network comprises of components such as circulation pumps, substations and pipelines. The flow in the pipeline is based on the temperature drop, pipeline diameter, length and heat requirement. Large diameter pipes have higher temperature drops due to higher surface area and friction caused by turbulent flow (Lindgren, 2015). The smaller diameter pipes have less temperature drop but their capacity is limited. The network strives to have low return temperatures this means large temperature drop and low flow. The higher the temperature difference the higher is the capacity in the network (Woerden, 2015). The flow of the warm water for the residential buildings varies on the demand. It is estimated that flow varies from 0.3 to 2.75 liters per second for demand generated from a single to 250 apartment residence (Euroheat, 2008).

The pressure drop in the pipeline is controlled by the booster pumps. The pumps ensure a flow of water and consequently heat in the pipeline. The pressure in the boiler at local distribution point is around 320 kPa and at consumer level is 360 kPa. In case of increased demand for the heat the flow rate at the boilers is adjusted so that the heat exchangers do not draw heat from other network. The heat is metered by volume delivered to the customer and energy consumed (Danfoss, 2019).

3.1.2 Institutional and economic characteristics

In the Netherlands, both government and private companies own the parts of district heating value chain. The usual trend in the heat market is towards a vertical integrated market. Oei (2016) highlights the fact that in 2009, out of the thirteen district heating networks, four were integrated, whereas in 2015, the number rose to nine. The Utrecht's district heating network is an example of vertically integrated network where Eneco produces, owns and operates the heat network. In some regions a public-private utility cooperative owns and operates the network (CE Delft, 2009). Another market model seen is a single buyer model, wherein multiple producers are present, and a single firm buys from these producers to supply heat to the consumers. Rotterdam follows a single buyer model where the heat network in the north Rotterdam is owned and operated by Eneco and in south by Warmtebedrijf Rotterdam.

The current end user price regulation sets the price of heat for the consumers. There is no competition in the market and consumers are protected by the 'Not more than other (NMDA) principle under the heat law. The producers and distributor get into an agreement setting price per GJ of heat. The consumer are charged a connection fee, variable cost depending on the usage.

3.2 The Gas network systems

The first natural gas reservoirs in the Netherlands were discovered in 1948. Later in 1950's the gas fields of Groningen were discovered which were one of the largest gas fields (2.800 billion m^3) known in the world. The low-cost and easy availability in large quantities natural gas from these fields replaced the dependence on coal and oil, and its export to neighboring countries generated substantial revenues for the Dutch government (Correljé, van der Linde,

& Westerwoudt, 2004). By 1968, all municipalities in the Netherlands were connected to the natural gas grid.

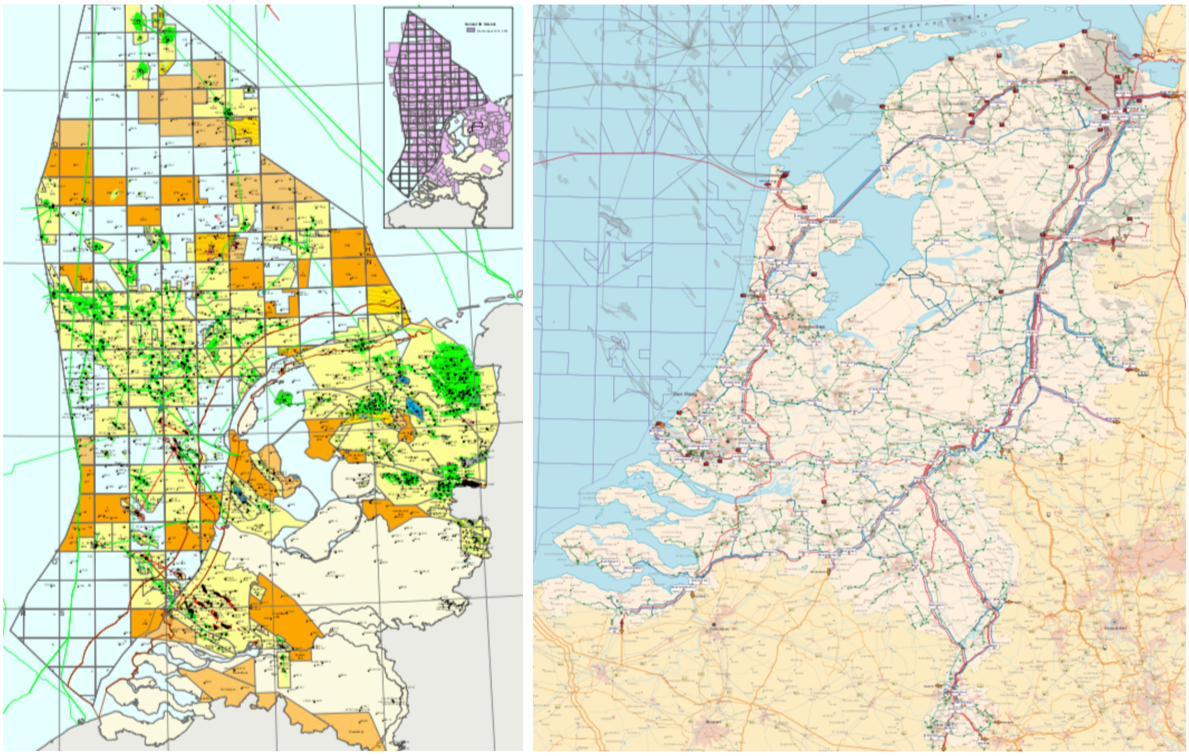

Figure 12: Groningen gas fields in green color (left) and Gas transport network (right). Adapted from (TNO, 2001) and (Gasunie Transport Services, 2015) respectively.

3.2.1 Technical characteristics

The characteristics of the gas commodity determines the transport network components and their interaction. Le & Loubar (2012) identified gas composition, dynamic viscosity, thermal conductivity, speed of sound, refractive index, density and compressibility as these physical characteristics. Natural gas is mostly composed of methane gas with a mix of other hydrocarbons[6]. The composition of this mix determines the quality of the gas[7].

Flow. The viscosity of natural gas varies proportionally with temperature. An increase in viscosity leads to decrease in flow of gas in the pipeline. The flow of gas is also directly dependent on the thermal conductivity of the gas. This flow thus can be described (in m^3h^{-1})

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[6] Natural gas is composed of mostly methane (90%), and low percentages of ethane, propane, butane, pentane, nitrogen, carbon dioxide, hydrogen sulfide, helium and water. The percentage composition of these components vary across fields of natural gas (Saikaly, Rousseau, Rahmouni, Le Corre, & Truffet, 2008)

[7] The quality of gas is understood thought the calorific value of gas. In Europe the calorific value of natural gas is approximately 11.4 kWh/m^3. It is measure by Wobble index.

as a function of the above mentioned characteristics as following:

Equation 1: Equation for flow of gas in a pipeline. Adapted from Le & Loubar (2012).

$$Q = C\frac{Tn}{Pn}\sqrt{\frac{(Pi^2 - Po^2)D^5}{fSLTZ}}$$

Where: C is a constant, Tn and Pn are the standard condition of temperature (288 K) and pressure (0.1 MPa). The Pi and Po are the inlet and outlet pressures, D is the diameter of the pipe, f is dimensionless friction factor, S is the specific gravity of the gas, L is the length of the pipe, T is the temperature of the gas, Z is the dimensionless compressibility factor.

The characteristics of speed of sound and refractive index are critical in identifying the pressure drop in the pipeline. Natural gas is lighter than air and is in gaseous state at temperatures above -162°C. Being in gaseous state at room temperature natural gas is a compressible fuel. It is therefore transported via high pressure pipelines from the production well to the consumption points.

Pipeline. The gas pipelines network along with components move the natural gas. These pipelines are designed keeping in mind the impact of critical factors (such as temperature, pressure on the gas flow) emerging from the physical and chemical characteristics of the gas. In case of the Dutch gas sector, the transport pipe system from the production well are divided into two grids: a main transport pipeline grid(*hoofdtransportleiding or HTL*), and a regional transport pipeline grid(*regionaaltransportleiding or RTL*)[8].

The total length of HTL pipeline is 5,330 km and of RTL is 5,926 km. The HTL operates at a high pressure ranging from 65 – 80 bars while the RTL operates at a pressure of 40 bars (Gasunie, n.d.). The HTL is linked with the network of TSO's outside the national border, producers, domestic end users, storage facilities and regional network operators via gas receiving stations. The temperature of the transported gas is usually 7°C and varies in the range of 0 °C to 50 °C based on the ambient temperature of the soil and requirements. The RTL is fed by the HTL and connects to the network of regional network operators (DSOs) and small industries.

Network components. Other components of the gas network include: compressor stations, mixing stations, reducing stations, valve locations, gas receiving stations, interconnection points, and measuring and control valve stations (for RTL) (Gasunie, 2014). Figure 13 shows the transmission and distribution part along with the network components of the Dutch gas grid. The size of the pipeline across the supply chain varies with the diameter of the pipe

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[8] The HTL pipelines are of two types, one carrying low calorific Groningen gas (G-gas) and other carrying high calorific gas (H-gas). The two are connected via blending station where Hydrogen and Nitrogen is added to H-gas for supplying into the G-gas HTL.

depending on the pressure inside the HTL and RTL.

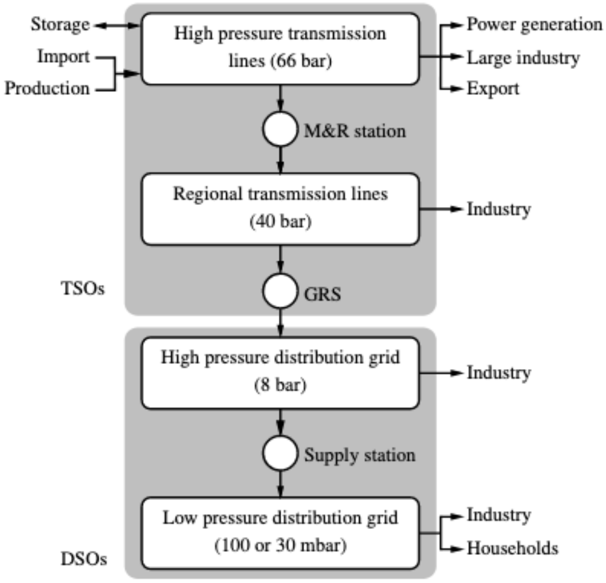

Figure 13: The Dutch gas grid supply chain. Adapted from (Weidenaar, 2011).

The speed of the gas maintained in the pipeline is usually 20 m/s (Gasunie, 2014). The metering and regulating (M&R) station, gas receiving station (GRS) and supply stations decrease the pressure to supply further into the network. In case of loss of pressure and temperature in transport due to leakage or other disruption the compressor stations can restrict the impact to local area by adjusting the flow and direction of the gas. As the single point failure is managed locally upstream without impacting the rest of the network downstream, the network topology design is linear upstream and radial connected mesh downstream.

Storage. As the natural gas is compressible in nature it is possible to store it in underground depleted aquifers and oil and gas fields and in overhead tanks as liquified natural gas. It can also be stored within the pipeline as linepack storage by varying the pressure in the network. In addition to providing supply cushion, the storage option renders vital flexibility in case of constraint on the pipeline (Role, 2017).

The natural gas system is not vulnerable to weather related incidents as the network is mostly underground and protected from damages. The system is therefore more resilient and robust than other network infrastructures such as electricity and telecommunication.

3.2.2 Institutional and economic characteristics

Across the natural gas value chain the ownership of the stakeholders in the gas and transport network was unbundled through various regulations over period of time[9]. At the production level, a coalition of the partnership (NAM or Nederlandse Aardolie Maatschappij) of the Dutch government (represented by EBN, 'Energie Beheer Nederland), Exxon and Shell owns the exploration and production right of natural gas in the two field types: large fields, i.e., Groningen and the small fields. The Transmission Service Operator (TSO) is responsible for the network safety, reliability, operations, transport capacity, maintenance of connection with national and international networks, balancing the network and ensuring supply of gas for temperatures as low as -17 °C[10]. The Distribution Service Operators (DSOs) are responsible for ensuring the efficient, safe and secure delivery of gas through the distribution network.

The shippers can access the gas network operated by the GTS by booking transport capacity at entry and exit points. There are eight LDC's in the Netherlands who own their separate network and are connected to the GTS's national grid (refer Figure 14). The transported gas in the network is owned by the shippers who are licensed program responsible parties. The shippers put in and extract the gas out of the network from entry and exit points.

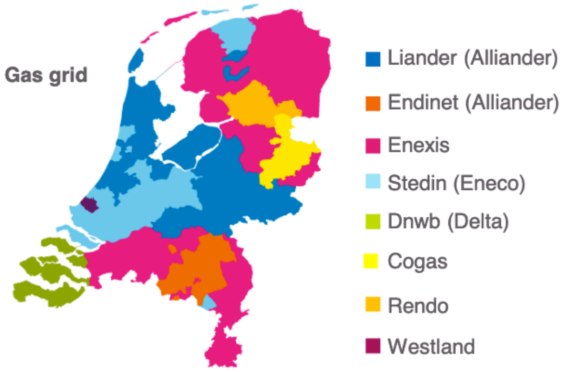

Figure 14: Gas DSOs and their regions of supply in the Netherlands.

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[9] The gas sector is regulated by the Gas Directives that set the framework for transmission, distribution and supply. The first directive laid out that pipeline access must be provided in a fair and open manner to achieve a competitive market. The second directive, defined the Third Party Access and regulations for its implementation. As an interpretation of this directive 'ex ante' set of rules were defined. The third directive, established a harmonized rules across the EU countries and unbundling of transmission from generation. This opened up the market for shippers who could access different networks following a set of procedures and paying a regulated tariff (Hallack & Vazquez, 2014b). In the Netherlands, shortly after the acceptance of the first directive, in 1998, a draft proposal for the new Mining Law was published. This culminated in the passing of the Gas Act of 2000. The Netherlands Authority for Consumer and Market (ACM) enforces the provisions in the Gas Act through regulation of the gas sector.

[10] Sourced from: https://www.gasunie.nl/en/what-gasunie-does/gas-transport

Balancing. The multiple shippers are allowed to contract capacity in the network to transport the gas to its destination. Once contracted, each shipper has to make use of the capacity in order for the system to remain in balance[11]. In case of network imbalance, the GTS evaluates portfolios of shippers and takes corrective action by analyzing the System Balance Signal or SBS (which is total of all imbalance signals from different portfolios) under the Balancing regime. The SBS signals determine the four types flexibility zone[12] of the transport network. The zones also provide for the Linepack flexibility service (LFS) for the shippers. Those shippers with imbalance make use of the buffer available and pay for the linepack flexibility service. The Figure 15 shows shippers using LFS for buffering and maintaining POS as 0. The shippers pay for the imbalance based on the predetermined tariffs set by the GTS and ACM.

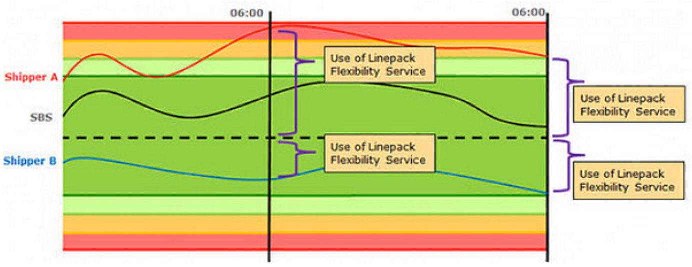

Figure 15: Linepack flexibility in a gas transport network and different zones[13].

Tariffs. The ACM also sets the tariff for all system operators every year. Based on these tariff GTS charges for tasks such as transportation, balancing, quality conversion, connection and maintaining existing connections[14]. The charged by the DSOs are based on the annual consumption (fixed charge) and the capacity used (European Commission, 2015). The ACM recognizes the natural-gas network as ‘natural monopoly’ where competition is limited or nonexistent. It designed an incentive-based regulatory scheme with goals deriving from the Dutch and European legislation (ACM, 2017). The four primary regulatory goals are as shown below in Figure 16.

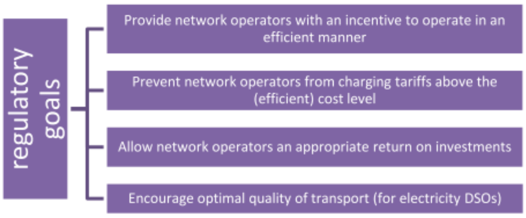

Figure 16: Regulatory goals for Electricity and Gas network.

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[11] The transport network is considered to be in balance when there is correct pressure in the network and there is a balance between the volume of the gas that leaves the market and the volume of the gas that enters the market.

[12] Green zone – no balancing required; Light green zone – some balancing done under certain circumstances; Orange zone – balancing performed, Red zone – balancing performed and in extreme case may force shippers to inject or eject all the gas from the network.

[13] Sourced from: www.gasunietransportservices.nl

[14] Sourced from: www.acm.nl/en/publications/tariff-decision-gts-2019

Under these regulatory goals the revenues of the operators are set before regulatory period (which is usually 3 to 5 years). This allows for scope of efficiency as the system operators may keep the resulting profits. The capping of revenues of operators also safeguards customers from being charged high tariffs. The annual income (TI_t) of the operator is based on the total income in previous year ($TI_{(t-1)}$), consumer price index (cpi), quality parameter (q) and x-factor (x) which is the price differential. The equation below shows the annual revenues formula:

Equation 2: Total income for a network operator.

$$TI_t = \left(1 + \frac{cpi - x + q}{100}\right) TI_{t-1}$$

The base revenue for GTS is set as the estimated cost level to ensure efficiency gains for the customers. For the DSO's the revenues are based on the average costs of the system operator itself. The consumers pay for the transportation of gas, contract capacity, periodic connection fee and administration costs (Enexis Netbeheer, 2019).

3.2.3 IDEF0 model of gas network systems

The technical, institutional and economic characteristics discussed in the previous section are contextualized in the IDEF0 functional model. A simple A0 level of IDEF0 model shows the input, control, mechanism and output for gas network system. The input for the system is natural gas which is extracted from subsurface. Its extraction and subsequent supply is controlled by the gas regulations and directives. The mechanisms of producers, consumers and network operators perform the activity to supplying gas in the network (Figure 17).

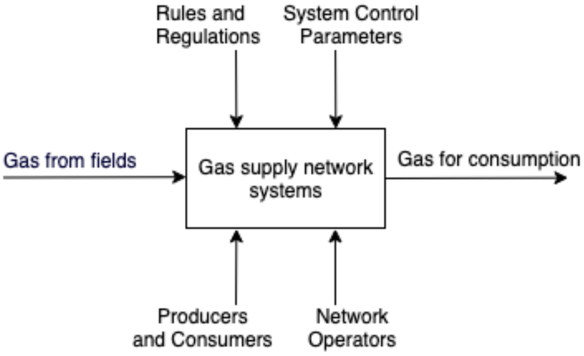

Figure 17: A top-level IDEF diagram of the gas network systems.

The context diagram of gas network systems presents a simplistic view of the system. In such a simple model drawing similarities and differences between the different networks is difficult as there is limited information presented. We therefore decompose the present A0 level IDEF model represented in context diagram further into multiple sub-systems. The gas network system is thus further into sub-systems with five main activities (Figure 18):

- ◊ Produce Gas
- ◊ Transport Gas
- ◊ Store Gas
- ◊ Distribute Gas
- ◊ Consume Gas

In the '*Produce Gas*' sub-system the producers extract natural gas from the gas fields through processes that are regulated under the Dutch Gas Act. Therefore, the input for this sub-system includes various sources of natural gas extraction (that is Groningen Gas fields and offshore Gas fields), mechanism includes the gas producing companies (NAM, EBN, GasTerra and others), control includes the Dutch Gas Act and output as gas that is exported and transported into the gas network.

The connections between the sub-systems are made based on the flow of gas in the network system. The other connections include flow of information and finances amongst the sub-systems. The system is controlled by the regulations and rules defined by EU directives and the Dutch Gas Act. Temperature and pressure is also identified as a control since they are critical to the network (Section). GTS, Gasunie, NAM, EBN, and ACM interact amongst each other as mechanisms in different sub-systems through transfer of gas, information and financial transactions. Detailed explanation of the activities, inputs, control, mechanisms and outputs for each of the sub-system is presented in Appendix C.

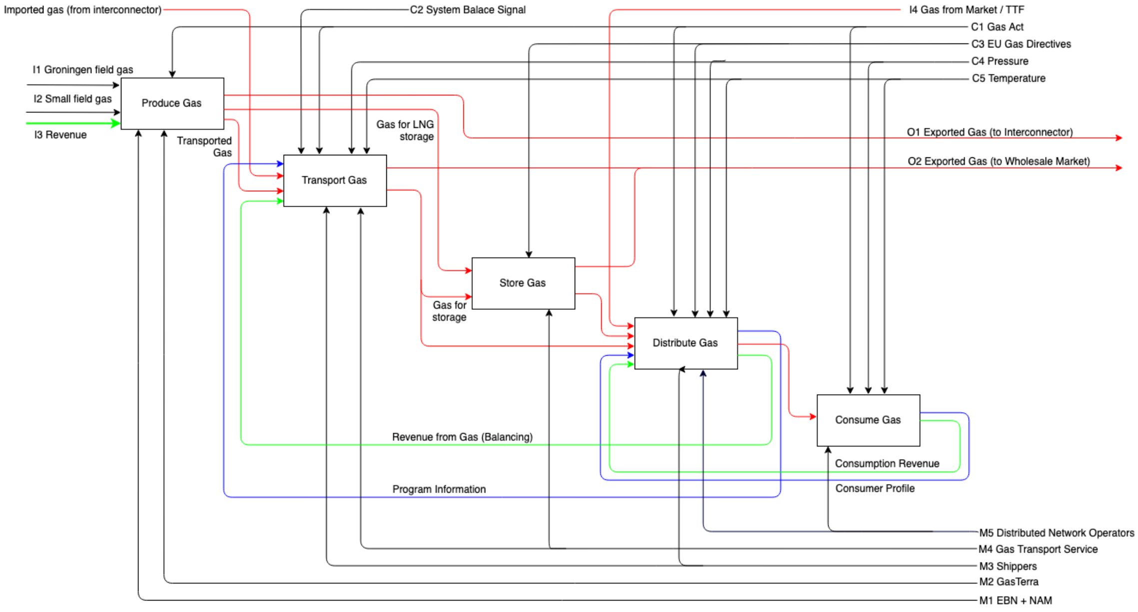

Figure 18: IDEF0 model diagram of gas network system.

Observation. In the IDEF0 model of the gas network systems we see observe interesting details. These are as described below:

◊ Transportation and distribution systems have a number of stakeholders shown by multiple mechanisms arrows and various rules and regulations shown by multiple control arrows.

◊ There are multiple input and output to the storage systems in supply of gas.

◊ Three different flows are seen in the model. These are the flow of gas, information and money each highlighted in red, blue and green colors respectively.

Interpretation. The observations presented above from the IDEF0 model shows patterns and characteristics as following:

◊ Transportation and distribution has market competition with multiple stakeholders seeking access to a single network. Therefore, we see rules and regulations, and other control parameters being critical for these sub-systems.

◊ The importance of storage in the network systems shows that there is *seasonality of demand* and the network ensures a *security of supply* through necessary addition of storage in the network system.

◊ The *flow of commodity, information and money* shows that the characteristics of the flow, that is speed, direction, control are critical to the gas network systems design. Each sub-system is linked to the flows from other sub-system and therefore any changes in one might impact the flows for other sub-system.

We showed from the above IDEF0 model that it is possible to represent the gas network system through sub-systems and various connections. The representation provided an insight into critical sub-systems, connections and flows for gas network.

3.3 The Electricity network systems

3.3.1 Technical characteristics

Electricity is defined as the presence and flow of electric charges at the speed of light. The electricity generated at the source is at high voltage and is transmitted either as alternating current (HVAC) or as direct current (HVDC) depending on the distance of transmission (Cory, 2002). A major difference between electricity and other sources of energy is that it cannot be stored. Although it can be stored in batteries, at present, the performance and inconvenience make it an impractical solution for handling the current demand (Pérez-Arriaga, 2013). Another characteristic of the electricity is that it flows through the path of least resistance. This means that the pathway to transmit electricity cannot be chosen and it determined by the laws of physics.

The characteristics of electricity make it a resource that can be transmitted and traded instantaneously irrespective of the location and source of production. The ease of generation allows it to be produced at remote location and in small scale. However, these characteristics also mean that the electricity system must always have a in balance in supply and demand. Any disturbance caused by the failure of even a single component at any point in the network can affect the entire system almost instantaneously. Adding to that, as the electricity grid network is highly interconnected the disturbance may cause reconfiguration of the flows across the network (Pérez-Arriaga, 2013).

The electric power systems like other energy systems comprise of production, transmission, distribution and consumption. The electricity is transported through the high voltage transmission grid over large distances. The Netherlands has four main transmission grids of 380kV, 220kV, 50kV and 110kV. The 380kV grid is connected via interconnectors to the grids of the neighboring countries. The Figure 19 illustrates these different type of grids in the Netherlands. The distribution grids operate up to 50kV. The alternating current in the grid is operated at a grid frequency of 50 Hz. If the demand increases than supply then the frequency decreases (as more power is taken from rotational energy of generators).

Figure 19: Electricity transmission and distribution network in the Netherlands[15].

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[15] Sourced from: www.infra.tbm.tudelft.nl

The robustness of the network is ensured through a n-1 principle which refers to a systems that consists of two circuits that ensures service in case of a failure in one of the two circuits. The Figure 19 also shows how the multiple loops in the grid ensures reliability of service.

3.3.2 Institutional and economic characteristics

Post the EU Electricity Directives and its implementation via the Electricity Act the electricity market is completely unbundled in the Netherlands with competition in production, whole trade and supply, and retail of energy. The electricity transmission network is operated by TenneT, which is the transmission service operator (TSO), and is owned by the Dutch government. The TSO is required as per the Electricity Act to operate, maintain, build, extend existing electricity network, secure safe, reliable and efficient electricity transport. It is also responsible to balance the system and ensure security of supply through program responsibility (De Keijzer et al., 2016). The TSO is also in charge of the interconnectors and ensures the capacity availability for the cross border trade through the APX electricity markets and network congestion.

There are seven DSO's[16] in the Netherlands operated by various limited liability companies providing program responsibility for the customers. Liander, Enexis and Stedin own almost 85% of the market for electricity distribution (Figure 20). Some networks are also owned by Delta and Eneco. All the distribution companies are owned by the municipalities as complete privatization is not allowed as per the Dutch law (Vries et al., 2018). In addition to measure the electricity consumed through energy program, their other tasks are similar to the TSO's but for the local distribution network.

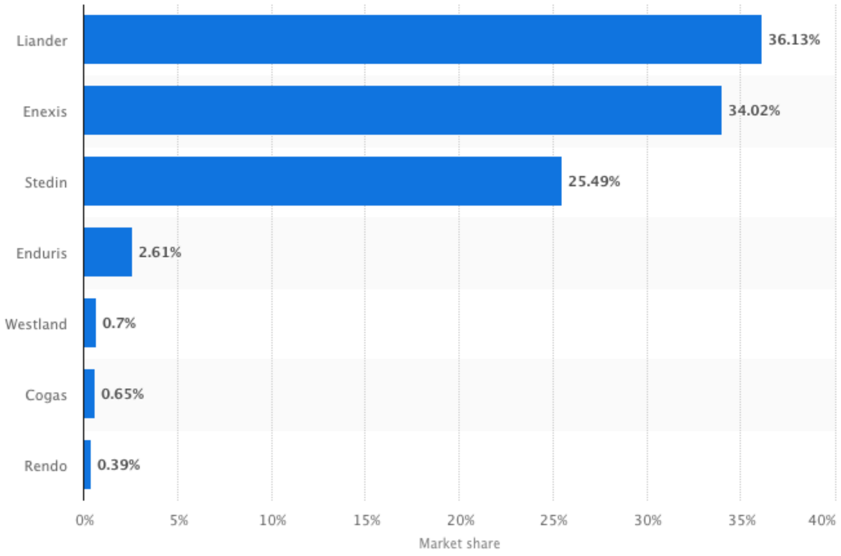

Figure 20: Market share of electricity Distribution System Operator in 2016[17].

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[16] Cogas Infra & Beheer, Enduris, Enexis, Liander, RENDO, Stedin and Westland

[17] Sourced from: www.statista.com

The access to the electricity network is through third-party access system. The technical system and access conditions are codified under the Network Code, System Code, and Metering Code (De Keijzer, Jaap; Kleinhout, Arjan; Van der Hoeven, Claire and Di Bella, 2016). The ACM is responsible for ensuring the regulations are followed by the system operators. The interconnector capacity for cross-border trade is auctioned off by Joint Allocation Office and is commissioned by the TenneT itself.

Tariff. The regulatory goals of electricity network are similar to those of the gas network (as shown in Figure 16). The tariff structure evolving from the regulatory goals calculates the connection and transportation tariff, and the tariffs for measuring household consumption and network access condition. The transmission tariff is independent of the location from where the electricity is generated, connection at which it is put in the network and location at which it is received. It follows the ‘postage-stamp tariff’[18] structure.

The ACM set the maximum rates for transmission of electricity and connection to the transmission grid for network operators using the *cpi - x* formula. The ACM in consultation with the TSO’s and DSO’s first identifies the individual efficiency factor of a network operator, sector productivity factor and the projected weighted cost of capital (the WACC) to. In second step, the x-factor that determines the annual efficiency deduction that an operator must apply to its revenues is calculated. Next, the q-factor (for DSOs) that represents the quality factor are determined for a period of three to five years. Annually, the operators submit their proposal for tariff based on the tariff structures and formula. The ACM then sets the final tariff for each of the network operator. The end-consumer pays for transmission tariff, contracted capacity (KW) and transport volumes (KWh) (De Keijzer et al., 2016).

Balancing. The balance in the demand and supply is made through trading and balancing mechanisms administered by TenneT through forcing balanced energy programs. TenneT has operating reserves in form of power plants that can generate electricity on short notice to maintain required balance. The power is contracted through a balancing market at a price that is higher than the spot market price. This creates a push on the producers and consumers to not to deviate from the energy programs.

3.3.3 IDEF0 model of electricity network systems

The electricity network includes power production, transmission, distribution and consumption. All the activities are modelled into the boxes with separate inputs and outputs. The input for production activity are the primary energy source and revenue. High voltage power is generated as the output and fed directly to the transmission lines and send to the interconnectors. The voltage of the electricity decreases from as it goes from transmission lines upstream to consumers downstream. The high voltage power contracted in power exchange and bilateral market from the producers is delivered to large consumers. Smaller consumer

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[18] Postage-stamp tariffs are fixed tariffs for per unit of energy transmitted in a specific zone regardless of the distance, utility systems and without accumulating zone access charges.

contract power from the retailers through retail markets.

The context level IDEF model of the electricity network system shows primary energy source as input and electricity supplied to consumers for consumption as the final output. The process is controlled by the rules and regulations along with system control parameters. The mechanisms used for the electricity supply network system include producers and consumers of electricity, network operators and mechanisms for balancing and capacity management. A point to be noted in the context diagram for electricity is that balancing and capacity mechanism plays an important role in the system. This is understood from the characteristics of the electricity and critical nature of network described in the previous sections.

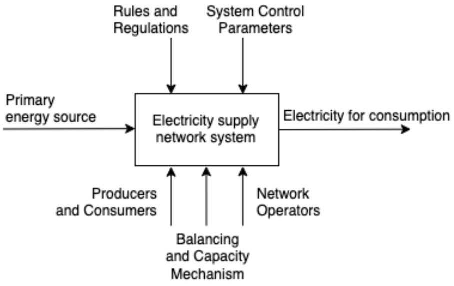

Figure 21: A top-level IDEF diagram of the electricity network systems.

To further investigate into the electricity network system we draw a second level IDEF0 diagram of the system. In this diagram we identify the major activities as following:

◊ Produce power
◊ Transmit power
◊ Distribute power
◊ Consumer power

The activities performed by each sub-system are connected by outputs, and control mechanisms. In case of ‘produce power’, the high voltage power is sent for transmission, distribution and also directly for consumption to large customers. This is seen as a output connection from the ‘produce power’ to ‘transmit power’, ‘distribute power’ and ‘consumer power’ in the model (Figure 22). Similarly, the consumption information from the consumers is sent back as a control input to the distributors and so on and forth to the producers. The system is controlled by the Electricity Directives, Acts and control parameters such as voltage and line impedance. A detailed explanation of the IDEF0 model for electricity network systems is presented in Appendix C.

Observation: In the IDEF0 model of the electricity supply network systems we see observe interesting details. These are as described below:

◊ There are multiple outputs and inputs for 'produce power' and 'transmit power' sub-systems.

◊ The consumers also generate power and feed it back into the distribute power sub-system.

◊ The power transmission requires mechanisms for balancing and capacity management.

◊ Three different flows are seen in the model. These are the flow of gas, information and money each highlighted in red, blue and green colors respectively.

Interpretation: The observations presented above from the IDEF0 model shows patterns and characteristics as following:

◊ The multiple output from the production points show that owing to the characteristics of the electricity and its network it is *easy to transport* outside the location where it is generated. Multiple inputs for the transmission sub-system also show that electricity is imported from other geographic locations and sent across the network to consumers. This shows that there is *no geographic dependency* for the electricity distribution.

◊ Possibility of consumers generating electricity and feeding it back to the system (though at lower levels of network) show that some part of *bidirectionality of flow* is possible in the network.

◊ The presence of balancing and capacity management mechanisms at the transmission sub-system indicates the high possibilities of system imbalance. This imbalance is a result of large amount of electricity being sent and received at the 'transmit power' sub-system with *lack of storage facility.* The physical characteristics of electricity makes it inefficient to store at present and therefore current systems depend on balancing the demand and supply in real time efficiently and not depend on storage.

◊ Similar to the flows identified in the gas network systems, the electricity supply network systems has three types of *flows*: electricity, information and money each represented in fig x in red, blue and green color respectively. Their interconnections show that the sub-systems are interdependent and changes to one may impact the other sub-system.

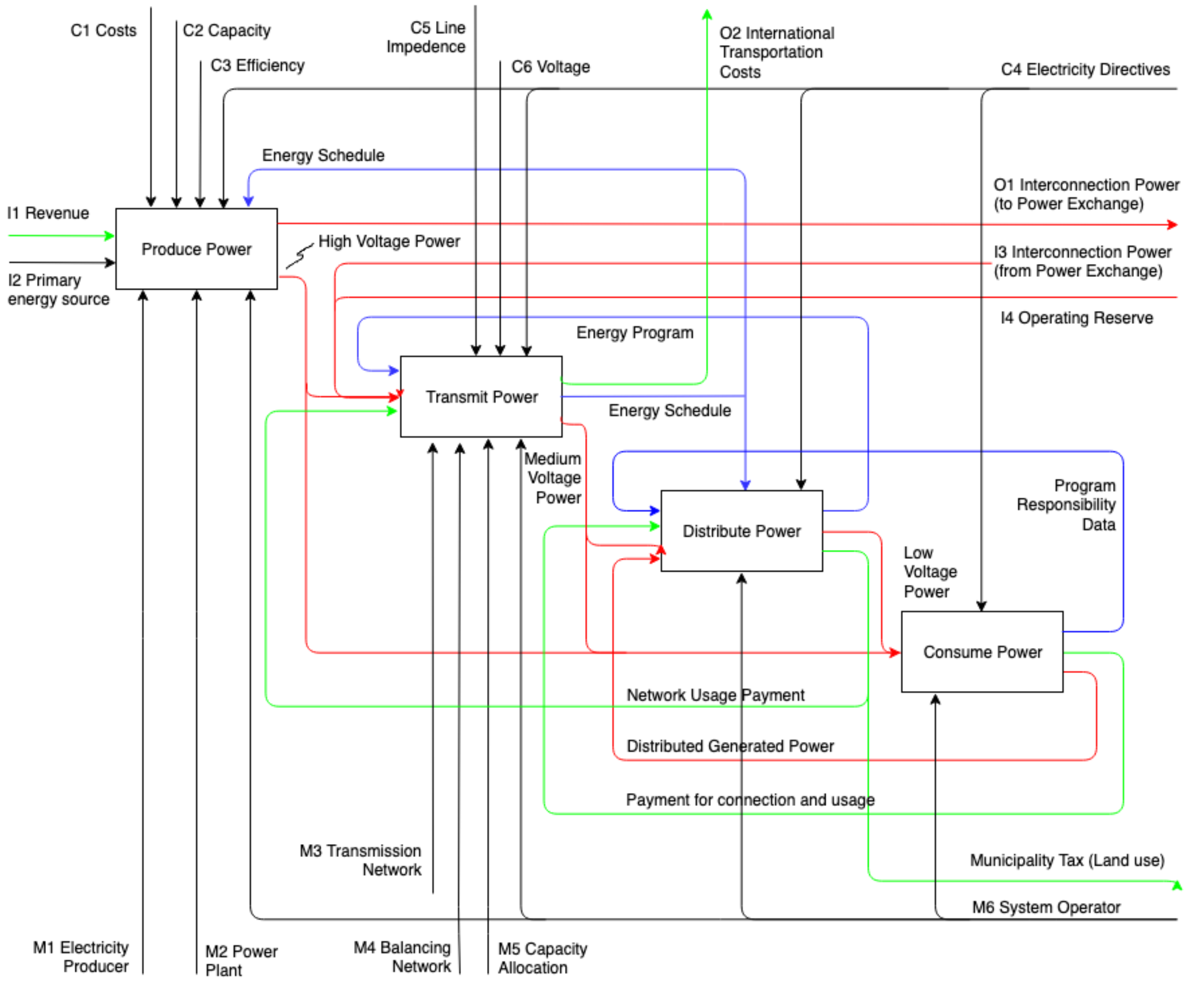

Figure 22: IDEF0 model diagram of electricity network system.

To summarize the discussion from above we can say that the electricity supply network systems can be represented as IDEF0 model with inputs, outputs, controls and mechanisms. We see that though the physical characteristics of the commodity makes it easier to transport across geographies but a lack of storability leads to need for balancing and network capacity management.

3.4 Water and wastewater network systems

3.4.1 Technical characteristics

Water as a commodity comprises chemically of H_2O and dissolved minerals. Due to the geographic endowment of the resource it requires pipeline transport infrastructure to bring from the abstraction point to the consumption points. Water is available in liquid form at room temperature (of 27 C) and this property is used to transport it across locations. It can also be stored in reservoirs for adding to the demand flexibility of the system. However, stagnation or poor flow rate of water in the pipelines and reservoirs leads to corrosion and bacterial growth that makes it unfit for drinking purposes (Suban, Cvelbar, & Bundara, 2010).

The pressure in the water pipeline at the point of delivery is 150kPa which is lower than the pipeline pressure of 313kPa (Geudens & Grootveld, 2017).

We use the term wastewater to describe the sewerage which consist of organic waste, liquid fats, and other throwaways. Some sewers also handle the excess drainage from rainfall (Hainsworth & Salvi, 2017). Due to composition of wastewater its speed of flow is slow and requires pumping to move around. On treatment, the liquid part is usually discharged in the rivers whereas the solid part (called as sludge) is used in farming as a fertilizer.

The key components of the water supply network are the service reservoirs, pipes, pumps and valves. In the United Kingdom, water networks are divided into Distribution Zones (DZs) and District Meter Areas (DMAs) (refer Figure). A single DZ may have multiple DMAs where the flows are measured. A DZ in the network corresponds to a single source of water such as a storage reservoir. The DZs are connect to the neighbors through a main trunk pipeline. The DMAs are separated from each other through boundary valves. These are opened and closed to restructure the DMAs, or provide supply in case of a failure (Hainsworth & Salvi, 2017). The water supply network uses the ring mains to ensure the continuity of the flow and an alternative route .

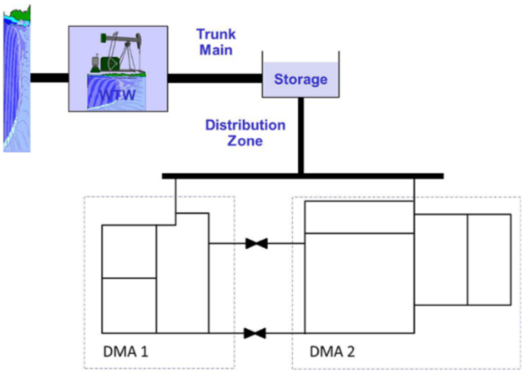

Figure 23: Water supply distribution network. Adapted from Hainsworth & Salvi (2017).

The wastewater network of sewage starts with a pre-treatment where a screen separates the big solid waste (such as paper, wood, rubber etc.) from the liquid waste. In primary treatment, a large tank then allows the remaining solid waste to settle down as sludge while the liquid fats and smaller solids get skimmed off from the top. Following the primary treatment the sewage is passed through a filter bed and activated sludge is added. This increases the oxygen level in the sewage and increases the decomposition process. In last stage of treatment UV disinfecting, micro filtration is conducted to control chemicals such as phosphorous and nitrogen.

3.4.2 Institutional and economic characteristics

The liberalization efforts of the water market in UK started in 1990s with the inset regime. The inset regime allowed for a third party to setup as a new vertically integrated service provider in an existing company's region of operation. The Water Industry Act of 1991 further allowed the developers to self-lay their infrastructure as per the standards and once completed the water companies was required to adopt it. This ensured that the costs of construction were kept minimum and standards were not compromised. The Water Act of 2014 was instrumental in introducing retail competition for all non-domestic consumes in the England.

At present there are around 12 water and sewerage companies and 9 water only companies operating across the UK (Figure 24). The regulation of the operation of these companies is done by Ofwat, Drinking Water Inspectorate and Environmental Agency. The wholesaler owns the network and provides water and sewerage service to the customers in the region. The retailers are responsible for providing value added services such as meter readings, grievance redressal etc. The wholesaler is paid for by the retailer who in turn sends the bills to the consumer.

The transactional exchange between the wholesaler and the retailer is managed by a market operator. In UK, the Market Operator Services Limited (MOSL) collects the tariff information from the wholesaler and meter readings from the retailers to calculate the daily charges and aggregates them in a monthly invoice for retailers. If a customer switches their retailer then the connection information of the customer is updated by MOSL with new retailer thereby making choosing of retailer an option and introducing retail competition. Introduction of a MOSL retail market has lead to lower bills, increased efficiency of water supply and improved customer services (OFWAT, 2018).

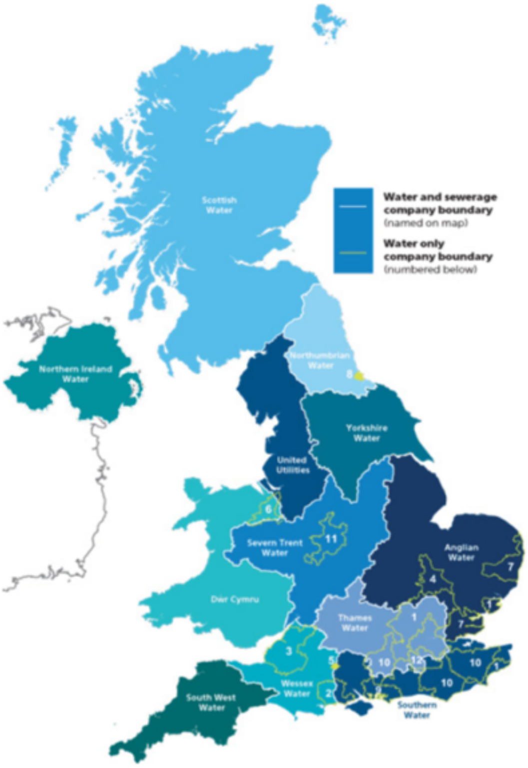

Figure 24: Wholesale operator in the UK water market.

The ownership of the distribution supply line varies based on the location of the supply pipeline. The operation and maintenance of the water main and communication pipe are the responsibility of the water company. The remaining downstream network is a shared or individual responsibility (Figure 25).

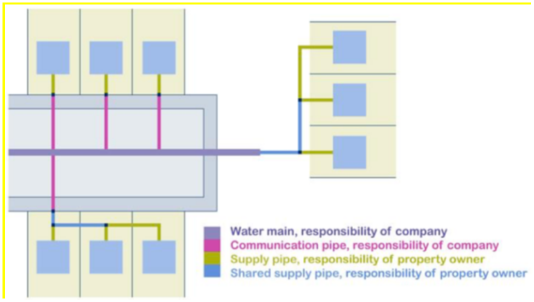

Figure 25: Water network and ownership in UK.

3.4.3 IDEF0 model of water and wastewater network systems

The water and wastewater network includes water abstraction and production from recycled sources and its distribution, consumption and treatment. The A0 level of the system can be represented with inputs as water from sources and supply it to the consumers. The process is controlled by regulations and technical parameters of the network. The mechanisms used for the water and wastewater network system include network regulators and various codes and agreements (Figure 26).

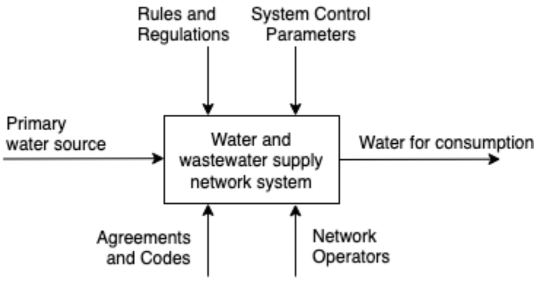

Figure 26: A top-level IDEF diagram of the water and wastewater network systems.

The context level IDEF model can be further expanded into sub-systems that carry four main activities:

◊ Produce / Abstract water
◊ Distribute water, and collect wastewater
◊ Consumer water, and produce wastewater
◊ Treat wastewater

The water is abstracted from primary source and sent for storage and distribution. The distribution sub-system further provides water to the consumer who consume and generate the wastewater. This generated wastewater is fed into the treatment units that feeds back water into the system (Figure 27). A detailed explanation of the IDEF0 model of the water and wastewater network is provided in the Appendix C.

Observation: The IDEF0 model of the water and wastewater network systems shows following details:

◊ The water produced and supplied is fed back into the system after treatment in a closed loop to the producers.

◊ The distribution and retail activities have multiple inputs, control inputs and mechanisms.

◊ Similar to the other network structures there are three different flows seen, mainly: flow of gas, information and money, each highlighted in red, blue and green colors respectively.

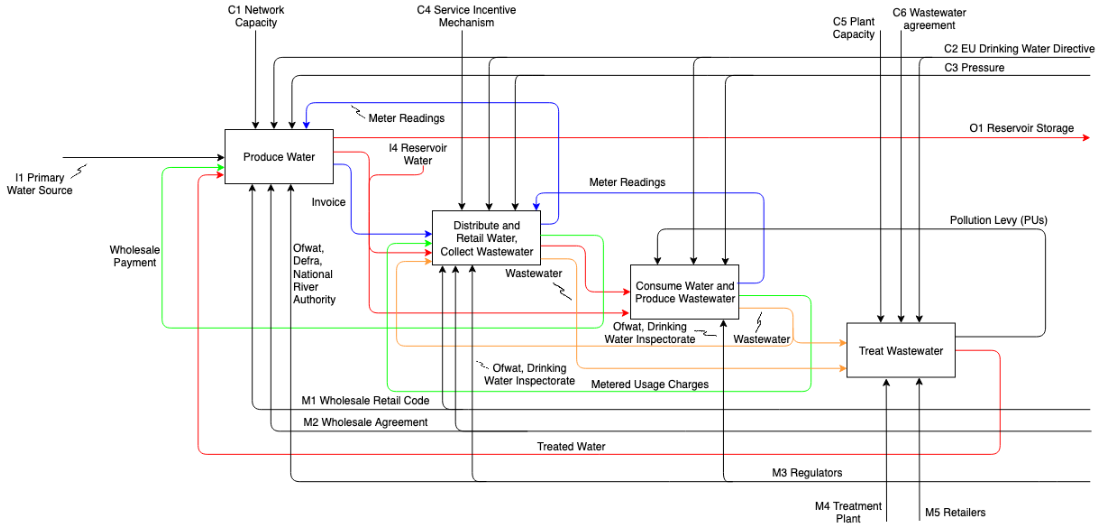

Figure 27: IDEF0 model diagram of water and wastewater network system.

Interpretation: The observations presented above from the IDEF0 model shows patterns and characteristics as following:

◊ The formation of *closed loop* of the network represents the dependency of network design on the characteristics of the commodity being supplied. The difficulty in transportation of wastewater makes it necessary to be treated locally through a separate network. This shows that based on the characteristic of the commodity (water or wastewater) its treatment and network also differs.

◊ As water can be *stored* in reservoirs and supplied in case of demand there is possibility of maintaining *balance* in the network through storage.

◊ The different *flows* across the sub-system and their interconnections show that there is interdependency amongst the various sub-systems in the network.

The IDEF0 model of the water and wastewater shows that the system can be represented as consisting of sub-systems, flows, inputs and outputs. A brief analysis shows that storage is a part of the system and provides necessary balancing to the system. The identification of flow amongst the different sub-systems shows that the system as a whole shares common characteristics with other network systems.

3.5 Similarities and differences in network systems

In the previous sections we saw various characteristics of the network infrastructures and their functioning as a system using IDEF0 models. These characteristics and specificities of these networks lead to emergence similarities and differences amongst them. Further, the similarities and differences are a source of transaction costs, network integration, coordination and market designs (Vazquez et al., 2012; Hallack et al., 2014a).

Based on the literature review on the key characteristics of network infrastructures and IDEF models are categorized in the following main categories, we observe the following:

i) Characteristics emerging from the flow of commodity, data, and money.

Matuschke (2014) and Carainic (2012) studied the importance of flows in a network and identified flow as a critical constraint in the network design. Amongst the different networks studied in previous section we see three different type of flows emerging: the flow of commodity, data (as information) and money. The flow of commodity is seen as a flow of mass in case of gas, water and wastewater, and flow of energy in case of electricity. For district heating we see it as a combination of flow of mass and energy and is quantified as Exergy (Gong, 2017). To draw comparison within the networks, the characteristics relating to the flow are categorized as directionality, flow control, speed of flow and losses in transportation. These are explained in detail as below:

Bidirectionality of flow of commodity. It is defined as the ability of the flow of commodity to change or reverse its direction. In heat networks the flow is of hot water flows from the source to the consumption point. In gas networks, the flow if of gas molecules from one point to the other. In water and wastewater network, there is a physical flow of water and wastewater respectively in the network. In case of electricity, there is no physical flow but the vibration of particles transport energy across the network. In this discussion the bidirectionality of flow is defined as ability to reverse the flow of heat in case of heat network, reverse the flow of gas, water and wastewater (in case of gas, water and wastewater respectively) and reverse the direction of electricity in case of electricity network.

In heating networks, Ancona (2015) presented that the bidirectionality has a direct impact on the type of the heating network as it affect the efficiency of the system. Schwele (2019) describes the need for gas network to allow bidirectional flow to meet the sudden off-take arising from variability of renewable generation. In case of electricity, bidirectionality is one of the issues the grid is focused on due to its impact on the entire network (Role, 2017). Therefore, the bidirectionality is considered as a critical factor the comparing the networks.

In light of above discussion, the heat networks at present have a unidirectional flow of heat and resemble the electricity, water and wastewater networks. In district heating, bidirectionality in form of cooling is present in the 5th generation district heating networks. But these are currently in pilot phase of development (Buffa et al., 2019). In case of electricity, we saw in IDEF model of electricity that the consumers generate electricity and it flows upstream to the distribution network. However, for the whole network the flow direction in the electricity network is one way only as all the components and circuit breakers are designed in a way to prevent backward flow to prevent damage to network devices (Appendix B). In case of the gas network there are provisions supporting the physical reverse flow of gas (GTS, 2011). The flow directions in the water and wastewater is fixed, that is the distribution to consumer and back to the source system (Frontinus, 2010).

Flow control. It is defined as the ability to control the flow of commodity in terms of direction and path in the network. The flow of commodity has an impact on the organization and design of the network infrastructure and its operations. Laajalehta (2014a) discussed the impact of the heat flow control in optimizing different type of network topology. Heydt (2011) and Sarkar (2019) highlighted that the flow impacts the network arrangement in electricity networks.

The direction of flow of heat carrier can be controlled in the heat network system similar to the gas and water and wastewater networks. In district heating the flow is controlled through circulation pumps and temperature drops (Laajalehto et al., 2014b). In case of Gas networks, the flow is controlled through pressure differential by components such as flow control and pressure control values (Berm et al., 2014). The flow in water supply network is controlled by pumps and valves (Leirens et al., 2014). In case of electricity, the flow path of electricity cannot be restricted due to the physical property of electricity. Also, as it flows at speed of light and through the path of least resistance it is difficult to control the flow (Appendix B).

Speed of flow. It is defined as the rate at which the commodity flows in the network. A network where the flow rate is high the network acts a single network where transactions and exchanges occur instantaneously. However, this characteristic also creates a vulnerability where a small network failure cascades instantaneously across the network. It is therefore an important network characteristic to analyze.

The speed of flow in heat network resembles with that of the gas and water and wastewater network. The maximum speed of flow in a district heating network at supplying heat at 100 degree is 1.3 m/s (Miltenburg, 2016). The speed of flow of gas in the pipeline is around 20 m/s (Section 2.6). As discussed in the previous section the speed of flow of water in the pipeline network is low and depends on the demand. In case of electricity network, electricity travels across the transmission lines instantaneously (RES, n.d.).

Transportation losses. The transportation losses are incurred during the transportation of commodity from production to consumption point. These losses results in additional costs due to network inefficiencies. Transportation loss is identified as an important activity parameter for energy network (Ghanadan & Koomey, 2005).

In case of transportation losses, the heat networks resemble the electricity and water networks with losses dependent on material of and the flow in the transport medium. Due to these losses the costs are incurred even when the resource is not being used. The transportation losses in electricity network are high and mainly due to the impedance of the transmission lines, distance to be transported[19], current and voltage (Bhattacharyya et al., 2008). The leakages in the water supply network are termed as high in the UK accounting for almost 20% of the water being lost in transportation[20]. The gas network faces loss in the grid in case of gas escaping the network or illegal withdrawal[21]. In case of gas network the losses due to pipeline transportation have been very limited[22].

The similarities and differences in above mentioned characteristics can be summarized as shown in the table below.

Table 3: Similarities and differences between heat, gas, electricity, water and wastewater network systems (set I).

S.No	Characteristic	Heat N/W	Gas N/W	Electricity N/W	Water and Wastewater N/W
1	Bidirectionality of flow	✓		✓	✓
2	Flow control	✓	✓		✓
3	Speed of flow	✓	✓		✓
4	Transportation losses	✓		✓	✓

A quick look at the table shows that in terms of flow and related characteristics the heat network systems resemble the water and wastewater networks. We now go further and investigate other characteristics of the network infrastructures.

ii) Characteristics related to storage and capacity in the network infrastructures.

The analysis of the physical characteristics of the commodity and IDEF0 models of the network infrastructures showed that storage and transport capacity differentiates between different

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[19] Sourced from: https://www.tennet.eu/e-insights/energy-transition/grid-losses/

[20] Sourced from: https://www.theguardian.com/environment/2017/may/11/water-companies-losing-vast-amounts-through-leakage-raising-drought-fears

[21] Sourced from: https://www.gasunietransportservices.nl/en/news/code-change-proposal-calculation-grid-loss-gas-published-by-acm

[22] Sourced from: https://semiannualreport2018.gasunie.nl/en/results-for-first-half-of-2018/safety-results

networks. In this section we identify some characteristics that related to storage and capacity such as network criticality[23], seasonality of demand, security of supply and storage and identify the similarities and differences between the networks.

Network criticality. A network is defined as critical if the failure of network component or section of it results in the threat of failure for entire network. In such a case the network is considered to have high network criticality. County (n.d.) identifies energy, water and waste water network system amongst critical infrastructures.

In terms of criticality the heat networks and gas network share similarities that both the distribution networks are not categorized as critical. In Netherlands, the heat networks are not identified as critical network infrastructure (HSD, 2015). The natural gas production is defined under critical category A[24], but its distribution infrastructure is under category B of critical infrastructures[25] (HSD, 2015). In UK, the water infrastructures are identified as critical infrastructures[26].

Seasonality and density of demand. It is defined as the variation in the demand of the commodity resulting from the peaks and low of demand annually. The understanding of seasonality of demand for network systems is critical for designing the flexibility for the system. Arnaud (2016) and Kong (2015) discusses the importance of seasonality of demand in context of electricity and gas market design respectively. In case of the heat network systems density of demand is a critical factor. District heating infrastructure requires higher density of demand than gas network infrastructures((Erik & Mortensen, 2003). We therefore look at the seasonality and density of demand as a characteristic for the different network systems.

The demand for heat, electricity and gas is known to varies across the season (Elshof, 2016). Whereas, the demand for water remains almost constant throughout the year (MEL, 1996). The density of demand characteristic is unique to the heat network systems as there is loss in temperature for the consumers who are further away in the network.

Security of supply: This parameters corresponds to the need for a secure supply of the basic utilities as a necessary means for the existence. If the utility is essential then it has security of supply as a principle driver in its design.

The district heating in the Netherlands is bounded by security of supply (Oei, 2016). Electricity also is considered as a basic need for the public and security of supply is a critical component (Ministry of Economic Affairs, 2016). The security of supply is considered critical in natural

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[23] Das (2018) identified energy storage systems to provide reliability, optimization and sustainability to network operators.

[24] Category A critical infrastructures are defined as infrastructures that have a high impact on the GDP, lead to casualties, survival and emotional problems or cascading effect.

[25] Category B critical infrastructures are defined as infrastructures that have low impact on the GDP, lead to casualties, survival and emotional problems.

[26] Sourced from: https://www.cpni.gov.uk/critical-national-infrastructure-0

gas network too as it is a commodity that is consumed locally and traded (Correljé et al., 2004). In case of the water supply and wastewater, the UK government requires security of supply for water supply to the customers[27].

Storage. It is defined here as the ability and possibility of deferring the amount of energy generated for use at a future moment, and storing it as it is or in another converted form (Europa, 2016). In case of network infrastructures, we saw in the previous discussions that some networks can store commodity in the network itself while some require external storage.

In context of storage, the heat network resemble the gas and water supply network as storage in the network or in external source is possible. Heat is stored externally in underground reservoirs, or as in molten salt batteries. Storage in form of thermal energy is also possible for district heating networks (Zuijlen, 2017). Properties of compressibility and density allows Gas to be stored within the network and outside as LNG (Section X). However, electric energy is not storable at present as it is not economical to store (Appendix B). The similarities and differences in above mentioned characteristics can be summarized as shown in the table.

Table 4: Similarities and differences between heat, gas, electricity, water and wastewater network systems (set II).

S.No	Characteristic	Heat N/W	Gas N/W	Electricity N/W	Water and Wastewater N/W
1	Network criticality	✓	✓		
2	Seasonality and density of demand	✓	✓	✓	
3	Security of supply	✓	✓	✓	✓
4	Storage	✓	✓		✓

A quick analysis of the table above shows that in terms of storage and network capacity characteristics heat network resembles the gas network systems.

iii) Other network characteristics

Some of the network characteristics such as the barriers to entry in the market for competition, geographic endowment, and commodity differentiation also share similarities and differences amongst the networks. These are as discussed below:

Barriers to entry: The high capital costs for production and sunk costs for transmission and distribution networks creates a monopoly which acts as a natural barrier for entry of new entrants in network infrastructures (Hallack & Vazquez, 2014a). Guichard (2018) suggests that inadequate measures of recovery of capital costs acts as an entry barrier by potential

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[27] Sourced from: https://www.gov.uk/government/publications/water-resources-planning-managing-supply-and-demand/water-resources-planning-how-water-companies-ensure-a-secure-supply-of-water-for-homes-and-businesses

entrants to market.

The barriers to entry for the district heating market are higher than electricity due to expensive transport network and losses that occur even when the resource is not being used (Woerden, 2015). Also, the water and wastewater systems are identified as sectors requiring massive capital investments (Defra, n.d.). However, the electricity market in the Netherlands have matured over time with liberalization. The introduction of green energy as a differentiated product has enabled retailers to capture higher willingness-to-pay from consumers (Mulder & Willems, 2019). We can therefore say that barriers to entry for the heat network are more similar to the gas and water and wastewater networks.

Geographic endowment: This refers to the spatial availability and accessibility to the resource. Resources that are available locally would require a regional network and may serve local markets better from those that are located far away. Scholten (2016) highlights that the geographic abundance of a resource has impact on the network topology and cross border flow.

The heating network and water network system share similarity in terms of regional network of production and distribution. District heating follows a district-focused approach by selecting the heat supply with the lowest social cost at local level (Stichting Platform Geothermie, 2018b). Similarly, the fresh water is available for abstraction across the UK through rivers, rainfall, and lakes (Environment Agency, 2008). In case of electricity, the Netherlands has a diverse geographic availability of the resources for power generation. The long coastline for wind power and significant natural gas is available for electricity production[28] from where it is transmitted across different regions. The natural gas reserves in the Netherlands are found in remote locations and off shore reservoirs (refer Section 2.6) and transported across.

Commodity differentiation. The term commodity differentiation is defined here as the importance given to the differentiated quality of commodity delivered. In case of some commodity such as electricity the consumers are not able to differentiate between the quality based on physical characteristics of commodity. However, in case of other commodities such as water supply the quality may differ for different providers.

Heat is seen as a homogeneous good with limited options of product differentiation (Bouw, 2017). Electricity is also seen a homogenous good and is sold at uniform pricing. The price differentiation arise from the consumer preference for usage (Sorin et al., 2019). The gas transported in the Netherlands is of different qualities; a high quality (H-gas) and low quality (G-gas or L-gas) based on the calorific values (DNV-GL, 2015). In case of water, quality is a critical factor as it is used for drinking purposes. Competition in the water market allowed for differentiation based on water quality (Cave, 2009). We see that in terms of commodity differentiation heat and electricity share similar characteristics.

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[28] Sourced from: https://www.hollandtradeandinvest.com/key-sectors/energy

Table 5: Similarities and differences between heat, gas, electricity, water and wastewater network systems (set III).

S.No	Characteristic	Heat N/W	Gas N/W	Electricity N/W	Water and Wastewater N/W
1	Barriers to entry	✓	✓		✓
2	Geographic endowment	✓			✓
3	Commodity differentiation	✓		✓	

We see that from the discussions that there are similarities and differences between the heat, gas, electricity, water and wastewater network systems.

3.6 Summary

In this chapter we identified the various technical, institutional and economic characteristics of the heat, gas, electricity, water and wastewater networks. Based on the literature research, expert interview and the IDEF0 model we narrowed down the characteristics into a list highlighting the similarities and differences amongst the network systems.

4 Design Variables for Heat Network

This chapter draws from the results of previous chapter and covers identification of design variables in Section 4.1. Next, the selected and rejected design variables are explored in brief in the Section 4.2 and Section 4.3 respectively. covers the various design variables in the market design. The discussion is concluded in Section 4.4 with a compiled list of the selected and rejected design variables for heat network.

4.1 Identifying design variables

As discussed in the previous chapter the heat network system has similarities with other utilities such as the gas, electricity, water and wastewater networks. Globally the utility markets have been restructured to add more competition at each stage of value chain. In case of the gas and electricity market in the Netherlands the unbundling was brought about through the EU Gas and Electricity Directives and subsequent Acts. The main driver for the restructuring being the policy objective of providing safe, reliable and affordable energy (MEA, 2016). Therefore, there is possibility of learning from the design choices made in these markets and considering them for the design space of the heat market.

It is interesting to see the variables that make up the market design of network infrastructures. At present there is extensive research on the market design for the electricity markets. We draw from the design variables for market design using the framework developed by Correljé and Vries (2008b). The framework presents thirteen design variables for the market design. These are as following: Degree of market opening, pace of market opening, integrated versus decentralized market, public versus private ownership, competition policy and horizontal unbundling, network unbundling, network regulation of tariffs and access conditions, congestion management method, arrangement with neighboring networks and interconnector congestion management, balancing mechanism, wholesale and end user pricing, capacity mechanism and position of regulator.

The design space for the heat network consisting of the design variables is restricted by the characteristics defined in the previous chapter. The characteristics acts as constraints and makes some design variables less relevant for the heat networks. In the next section we describe the relevant design variables and the excluded design variables for the heat network along with the characteristics that support or constraint their selection for design space of heat network.

4.2 Included design variables

The following section presents the design variables and choices that are included for the design space of the heat networks.

4.2.1 Degree of market opening

Degree of market opening refers to the introduction of competition at various sections of the market. Correljé & Vries (2008a) determined that competition in network infrastructures can be introduced by restructuring the market itself. This restructuring can be done at different levels of the network there by generating possible options for market structures. These are as discussed below:

Wheeling. In this case there is no restructuring, that is, the ownership and access to the network remains with a single market entity. In Wheeling, single monopoly in the value chain carries the resource around and is responsible for all the activities.

Single-buyer model. In this option there are many producers selling to one company that distributes (heat or other commodity) to consumers. Correljé & Vries (2008a) remarks that this is a disadvantageous situation for individual power producers (IPPs) since the purchasing company is also a producer in this case. This situation leads to exploitation as the purchasing company may exclude the IPPs. This option therefore requires a regulator to keep a check on the exploitation by network owner.

Wholesale competition. In this arrangement the producers are able to sell to many large buyers through long term contracts. However, as is usually in case of network infrastructures there is a single network owner and the wholesale competition leads to a competition for capacity amongst producers. This may in turn lead to resale of capacity in the market and if kept unregulated this would develop into a monopoly selling directly (Klein, 1996).

Retail competition. In the final form of market restructuring, the entire value chain is opened to competition. The consumers have choice to choose the retail service providers. In the Dutch energy market context the electricity and gas market operate with this method. However, an increased number of operators and transactions leads to high transaction costs in this arrangement.

Owing to the characteristic of *geographic endowment, speed of flow* and *transportation losses* The heat network systems are regional in scope. In such case it becomes interesting to see up to what extent can competition be introduced in such a network. Söderholm & Wårell (2011) discussed the possibility of both a single buyer model and a monopoly in the heating network. We therefore consider the variable of degree of market opening as priority for design space.

4.2.2 Integrated versus decentralized market

The initial market with limited number of competitors provides an immediate possibility of an integrated heat markets. Specially, if the design choices include wheeling and single buyer models integrated markets would be best fit. In integrated market the network operator operates a mandatory pool in which the economic and technical aspects are combined. In case of decentralized markets the system operator is responsible for technical function and the supply and demand is balanced in bilateral contracts or through an exchange (Vries and Correljé, 2008b). In case of decentralized markets the design choices of wholesale and retail competition emerge (Hunt, 2002).

The integrated market model followed in the US provides optimization and congestion management as a single entity is responsible for the technical and economic aspect of the network. In case of the Europe the decentralized market model makes use of models such as market coupling to optimize trade between two regions. The possible options under a decentralized market model includes bilateral contracts and exchanges (CE Delft, 2015). It is therefore interesting to see the impact of selection of integrated or decentralized market in the design space.

4.2.3 Public versus private ownership

Apart from liberalizing the access of the physical infrastructure, the ownership of the entire value chain of network infrastructure can be privatized in parts or whole. As in market restructuring of utilities it is not mandatory for the government to be a part of competitive activities (Correljé & Vries, 2008). The possible options for introduction of privatization can be through privatization of the production activities, transportation of the distribution activities and delivery activities. The regional characteristic of the heat network system makes the public private ownership an interesting design variable.

4.2.4 Network unbundling

Network unbundling can be described as the extent to which the network managers allow producers and other users to access their network. Klien (1996) identified the importance of unbundling of bottleneck facilities to introduce competition in the network infrastructures. There are three main types of unbundling; a) accounting, b) organizational and c) structural or judicial (Lowe et al., 2007). In accounting separation the cost allocations or the accounts are maintained separately. In organizational ownership a separate business unit is created and in structural separation entire section of the value chain is split into separate legal entities.

In case of heating network this variable is important as the third part access to the network is linked to the extent of unbundling. We therefore consider this as a priority design variable for the heat network design space.

4.2.5 Network regulation and tariff

The network regulations and tariffs depend on the variable of network unbundling and extent of public or private ownership of the parts of network. The second EU Directive provided option for a regulated third party alternative by enabling network access to the third parties on payment of a fixed tariff (Hallack & Vazquez, 2014a). It is usually the government or an agency that sets the tariff for a fixed period for the use of network. The tariffs components for the network are usually based on the marginal cost, or cost plus pricing.

The other alternative for network regulation is negotiated third party access. In case of negotiated third party access the parties enter into an agreement and decide for themselves the network tariffs. The role of the regulator is to step in cases when there are no agreements between the parties.

4.2.6 Integration with existing networks

Integration with existing network refer to possibility of physically connecting different network together. As the individual networks grow they generate the possibility of interconnections and benefit from the economies of scale and introducing competition. Integration also depends on the type of commodity and the requirement for robustness. However, every network operator and supplier may not be interested in interconnections if it threatens their position in the market.

The integration with existing network is selected as a relevant variable due to the characteristic of *commodity differentiation*. The ability to connect and share heat across network may present a design choice for the heat network.

4.2.7 Wholesale and end user pricing

In many markets the prices for the wholesale and retail are regulated in interest of the consumers. Various options such as setting a maximum price for a quantity of commodity yearly or restricting the revenues of the producers and distributors are used for end user pricing. However, policy decisions such as price-restrictions may lead to under investment in capacity by the generators (Correljé & Vries 2008). Therefore, the pricing is designed keeping in mind that it triggers new investments and keeps bills low for the consumers.

In case of the heat networks the pricing becomes a key variable as the price for the heat are at present linked to the gas under Not-More-Than-Otherwise (NDMA) principle. With the transition away from gas the end user pricing becomes an important variable to consider. It is therefore included in the consideration for the design space for the heat network.

4.3 Excluded design variables

As discussed at the start of the chapter some design variables are excluded based on the limitations set forth by the characteristics of the heat network. Although, these variables are not considered in further analysis we describe them in brief in this section.

4.3.1 Pace of market opening

The pace of market opening refers to the speed of restructuring the market. The market can be opened up at once by introducing full retail competition or through gradual processes (Vries, L; Correljé, 2008b). The pace of market opening for the heat network is broadly defined by the long term goal of the Dutch government to shift to district heating networks. Also, since the pace of market opening depends on the other variables such as degree of market opening and network access we exclude it from the study.

4.3.2 Competition policy and unbundling

The competition policy oversees the level of competition in the market. It includes a tradeoff between the scale and the scope of unbundling for competition in the market (de Vries et al., 2018). In case of extensive unbundling with high competition a regulator are required to ensure that companies do not exploit the consumers. The competition policy is a broader discussion that including other network infrastructures. As it is not exclusive to the design space of heat network is therefore excluded from the study.

4.3.3 Balancing mechanism

In decentralized networks it is difficult to accurately estimate the demand and supply for the utilities and therefore there will be instances where the system will be unbalanced. The network operators are responsible for maintaining a balance in the network. This is achieved through balancing mechanisms such as operating reserves, and balancing markets.

In case of the heat networks, drawing from the *characteristics of the flow* such as speed of flow allows heat network some flexibility. The possibility of *storage* of heat may provide as a buffer for the demand fluctuations. Based on these characteristics the balancing mechanism is excluded from the scope of the study.

4.3.4 Capacity mechanism

Capacity mechanisms provide for a way to influence the stakeholders to invest in the capacity to ensure the security of supply. Some mechanisms are also designed to control the volume of generating companies (Correljé & Vries 2008). Some of the capacity mechanisms include: capacity payments, strategic reserve, capacity requirement, reliability contract and capacity subscription.

In current scenario, as the production of heat and demand has not reached to an extent that the system is requires capacity mechanisms. Furthermore, the possibility of *storage* allows the network to store the excess heat for later use and thereby reduces the need for increasing the capacity. Therefore, capacity mechanism is not considered in this study.

4.3.5 Position of regulator

The position of regulator refers to the level at which the regulator operates. It can be at local, provincial or at national level depending on the extent of its participation in the sector. Looking at the current scenario the regulator (ACM) for all energy systems is at a national level. This is not expected to change as the position of regulator is a broader discussion common to other network infrastructures as well. Also, the position of regulator is relatively known to be ex-ante in case of a monopoly (Söderholm & Wårell, 2011). This variable is therefore not considered for further analysis.

4.3.6 Congestion management

Congestion may occur in network when the network capacity is inadequate to accommodate the flow of desired quantity of commodity. It is more prevalent in networks where; a) it is difficult to predict the demand and supply, b) lack of slack capacity in the network due to expensive capital investments and c) storage or buffering is not possible.

In case of congestion management for the heat networks, the characteristics of *geographic endowment*, *speed of flow* and *transportation losses* renders heat a regional commodity. Due to the localized nature, ease of *flow control* and *storage* it is easier to predict and manage congestions in the heat network. Congestion management is therefore excluded from further analysis.

From the above discussions we have identified the relevant design variables for the design space of the heat network. In the next chapter, we take a deep dive in these variables and generate a holistic design space.

4.4 Conclusion

In this section, first the design variables for the heat networks were identified. Further, from amongst the thirteen design variables seven were prioritized based on the characteristics of the heat network. There are as summarized in the table below.

Table 6: List of included and excluded design variables for design space of heat network.

#	Included design variables	#	Excluded design variables
1	Degree of market opening	**1**	Pace of market opening
2	Integrated versus decentralized market	**2**	Competition policy and unbundling
3	Public versus private ownership	**3**	Balancing mechanism
4	Network unbundling	**4**	Capacity Mechanism
5	Network regulation and tariff	**5**	Position of regulator
6	Integration with existing network	**6**	Congestion management
7	Wholesale and end user pricing		

5 Design Space for Heat Networks

This chapter charts our a design space for the heat network by contextualizing the selected design variables identified in previous chapter. The Section 5.1 on design choices goes into an in depth explanation of the design variables and their. The interdependencies between the design choices is discussed in Section 5.2. The chapter is concluded in the Section 5.3

5.1 Design choices for heat network

In the previous chapters presented a list of relevant design variables for the heat network by drawing from the gas, electric and water network systems. A combination of these design variables (DV) generates the design choices for the heat network. In this section we explore the selected design variable and their options along with their respective pro's and con's for the heat energy market design. The pro's and con's for the design variables provide an understanding of the impact of design choices in the design space.

5.1.1 Degree of market opening (DV 1)

As discussed in previous chapters, the present markets in the Netherlands for the electricity and gas are structured with retail competition. The water and wastewater markets in UK on the other hand are growing from a single-buyer market model. The heat markets have high barriers to entry owing to high capital costs. Also, the geographic endowment of the heat is more localized in nature. This similarity with the network infrastructures of gas, water and wastewater network makes the options 'wheeling' and 'single buyer model' possible for heat markets. The various options for the degree of market opening for heat network are discussed below:

Wheeling. It can also be considered as a case of monopoly as in this case there is a single producer who transports and distributes the heat in the network to the consumers. The consumers have no option of switching the provider.

The advantage of this option is that because of limited number of stakeholders it is easier to plan and manage such a network. From the regulators perspective as well, it is easier to monitor and regulate such network. However, the problem with wheeling in heating network is that it may lead to inefficient heat networks and poor quality of service due to lack of competition in the market.

Single buyer model. The single buyer model in the heat network can be seen as a model in which multiple heat producers provide heat to a single network owned and operated by one company. At present many district heating markets in the world follow wheeling and single buyer model with a single network operators.

The advantage of the single buyer model is that it is easier to implement since the ownership of network remains with a single company and all producers pool in the heat to the network. This also leads to low transaction costs in the network. However, similar to the wheeling model in this case too there is a single transporter and distributor of the heat. This may lead to inefficient networks and poor quality of service.

Wholesale competition. Over period of time as more participants enter the heat market wholesale competition option becomes possible. In such a case, multiple wholesalers compete to provide heat to large customers. In this option the small consumers still do not have freedom to choose suppliers.

The advantage of this option is that it is comparatively easier to implement (with respect to retail competition) and provides benefit of competitive markets to section of heat consumers. The challenge of this option is that as the number of stakeholders increase there is increased dependence on the heat consumption data leading to high transaction costs. Also, with multiple wholesalers of heat to the network there would be need for access regulation in the heat network.

Retail competition. In retail competition option for heat there would be multiple retailers trading heat in market and supplying to consumers. The customers would have freedom to choose amongst the suppliers and competition would lead to an increase in the quality of service delivered. The challenge with this option is that with multiple participants in the market the transaction costs would be high and there would a need for regulations for the heat market.

The introduction of competition at the downstream in retail competition would have to be matched with technological advancements to minimize the additional transaction costs of information flow. This problem provides an opportunity for technology firms to create new business models.

Table 7: Summary of design options for degree of market opening.

DV1	Design variable options	Pro's	Con's
1	Wheeling	◊ Easiest to plan and manage as heat and network owned by same entity ◊ Easy to regulate and expand	◊ Increased inefficiency ◊ Poor quality of service

2	Single buyer model	◊ Easier to implement ◊ Low transaction costs	◊ Scope for inefficient service as single supplier ◊ No incentive to invest in capacity as no competitor
3	Wholesale competition	◊ Easier to implement ◊ Customers benefiting from competitive pricing.	◊ High dependency on accurate data from consumers, retailers and wholesalers. ◊ High transaction costs due to multiple wholesalers, retailers ◊ Need for access regulation to the network
4	Retail competition	◊ Freedom to choose retailers ◊ Customers benefiting from competitive pricing and service.	◊ High dependency on accurate data from consumers, retailers and wholesalers. ◊ Need for access regulation to the network ◊ High transaction costs

5.1.2 Integrated versus decentralized market (DV 2)

In context of heat markets the integrated and decentralized market would depend on the competition in the market. With low degree of market opening that is in case of Wheeling and Single buyer model the heat markets would shape into an integrated market with one entity owning the technical and economic aspect. Whereas in case of high level of degree of market opening with competition in wholesale and retail bilateral contracts and exchanges may emerge in the heat market. This we see from the similarity of the characteristics of heat market with the water and wastewater markets.

The advantage for integrated market is that with low number of stakeholders the transaction costs are low and it is easier to implement by the regulator. However, in an integrated market model for the heat network the lack of competition would limit the possibility of increasing efficiency of the network. In decentralized market the presence of multiple stakeholder provides opportunity to have high quality of service and competitive pricing for consumers. The bilateral contracts and exchanges would ensure that the demand and supply are met in most economical way. The disadvantage of this option is that there is a dependence on the exchange of information since the technical and economic aspects are segregated. This results in high transaction costs in the network.

Table 8: Summary of design options for integrated versus decentralized market.

DV2	Design variable options	Pro's	Con's
1	Integrated market	◊ Easier to implement ◊ Low transaction costs	◊ Less efficient as lack of competition
2	Decentralized market	◊ Customers benefiting from competitive pricing and service.	◊ High transaction costs

5.1.3 Public versus private ownership (DV 3)

In case of the heat networks systems the ownership can be public, private or a combination of both for the production and network activities. In present case the Dutch ownership of the heat production and network is public and private both. The owners produce, operate and maintain their networks by themselves. Both the systems have their separate advantages and disadvantages. While with a public ownership the security of supply is guaranteed but the quality of service may not be efficient. On the other hand a private owned network may be efficient due to competition but it requires regulatory supervision to protect consumers from being exploited. In case of a combined ownership the network system benefits from the advantages of public and private ownership. However, the inclusion of multiple stakeholders makes this option difficult to implement.

Table 9: Summary of design options for public versus private ownership.

DV3	Design variable options	Pro's	Con's
1	Public ownership	◊ Easy to implement ◊ Easiest to plan and manage as heat and network owned by same	◊ Less efficient as lack of competition ◊ Poor quality of service
2	Private ownership	◊ Customers benefiting from competitive pricing and service. ◊ Creates impetus for innovation	◊ High transaction costs ◊ Requires regulation to check exploitation and ensure security of supply by private firms
3	Public – Private ownership	◊ Easy to implement ◊ Customers benefiting from competitive pricing and service.	◊ Difficult to initiate new projects as multiple stakeholders involved.

5.1.4 Network unbundling (DV 4)

As discussed in previous chapter the network unbundling is achieved through separation of network activities from production and delivery. The possible options of accounting, structural and judicial unbundling are applicable to the heat market.

Separate accounting. In case of accounting unbundling the network managers are required to keep separate accounts of the network activities from production and delivery in case of a vertically integrated market. The advantage of this form of network unbundling is that it is easiest to implement as no large changes are required to be made in the market structure. However, the network manager may in this case chose to deviate since the access to information is restricted to the network managers themselves.

Organizational separation. In case of organizational separation a separate business unit are formed for the heat production, network activity and delivery. The benefits of organizational separation is that it is more clear than the accounting separation since business units are different. However, even in this case as vertical integration is possible the business units may restrict information from the competition.

Judicial separation. In case of judicial separation the network operator is judicially separate owner of the network and its activities only. The restriction of the network owner to the network itself allows for competition in production upstream and wholesale and retail in downstream. It provides a transparent network system with equal access to information for all stakeholders. The disadvantage of judicial unbundling is that there is high transactional cost due to multiple stakeholder and their interaction.

Table 10: Summary of design options for network unbundling.

DV4	Design variable options	Pro's	Con's
1	Separate accounting	◊ Easiest to implement	◊ May not ensure competitive markets to develop ◊ Difficulty in monitoring by regulators information asymmetry
2	Organizational separation	◊ Comparatively higher transparency	◊ May not ensure competitive markets to develop ◊ Difficulty in monitoring by regulators information asymmetry
3	Judicial separation	◊ High transparency ◊ Easy to manage. ◊ Creates impetus to innovate	◊ High transaction costs ◊ Depends on the level of technological advancements in the heat industry

5.1.5 Network regulation and tariff (DV 5)

As discussed previously, in case of the heat network the access can be regulated as a negotiated third party access or regulated third party access In case of negotiated third party access for the heat network the supplier and the producer of heat enter into an agreement at price for the network tariff. Only in case of a disagreement or high tariffs for consumers the regulator may step in and intervene. In case of regulated third party access for the network the network operators are forced to allow other producers to access their network for a tariff calculated by regulators. The producers and network operators in this case have an incentive to increase their efficiency since the tariffs are fixed for a period by the regulators.

The tariff options include marginal cost and cost plus pricing. However, the marginal costs for heat network are known to not cover the costs of production due to inelasticity of demand. This may be favorable for the consumers but in the long term may lead the independent power producers to exit the heat market. In case of cost plus pricing the suppliers are ensured of their costs being covered and a fixed return on their investments. However, in this case the producers and network operators do not have incentive to increase efficiency and may pass on additional costs to the consumers.

Of the possible tariff arrangements under the regulated Third Party Access, price capping is the present method for the Dutch heat markets. This is based NDMA principle which ties the maximum price of heat to that paid by the natural gas users.

The negotiated Third Party Access does not seem to be a feasible option for the district heating market as network companies might not want to provide access to other producers to their network unless a regulation forces them to.

Table 11: Summary of design options for network regulation and tariff

DV5	Design variable options	Pro's	Con's
1	Negotiated third part access	◊ Less role for regulator as intermediary ◊ Easy to implement	◊ Possibility of gaming by the producer and network operator ◊ Difficult for network operator to provide access to independent producers
2	Regulated third party access	◊ Customers benefiting from competitive pricing and service. ◊ Creates impetus for innovation as firms try to minimize production costs	◊ Require regulatory bodies and constant monitoring.

5.1.6 Integration with existing networks (DV 6)

As the individual networks grow they generate the possibility of interconnections and benefit from the economies of scale and introducing competition. However, every network operator and supplier may not be interested in interconnections if it threatens their position. In case of the heat networks, the regional characteristics of the heat restricts the size of the heat networks. However, there is a possibility of interconnecting neighboring networks together and exchange heat over geographies.

The advantage of integration of heat networks is that it provides security of supply and as more networks are connected the economy of scale would make the heating economical. However, connecting different heat networks is a complex socio-technical problem with costs risk and dependency on political will (Appendix B).

Table 12: Summary of design options for integration with existing networks

DV6	Design variable options	Pro's	Con's
1	Integrated network	◊ Ensure security of supply ◊ Economies of scale as more heat producers can pool in heat.	◊ Complex socio-technical problem ◊ High financial costs associated ◊ Large risk of technology and political
2	Non- integrated network	◊ Low risk as regional network	◊ High costs ◊ Dependency on regional producers

5.1.7 Wholesale and end user pricing (DV 7)

As discussed previously the possible options for heat network for pricing can be either maximum price for consumer through regulation or capping the revenues of the producers and operators. In case of setting a maximum price or the heat based on external benchmark (such as gas in case of the Netherlands) the consumers benefit who have limited alternatives to district heating. However, price capping may not be efficient for customers with different demand. For the producers too, price capping may not reflect the actual cost of production which depends on the economy of scale.

In case of capping of revenues similar to the gas and electricity networks the revenue is set based on the consumer benefit and network efficiency for a predefined period (ACM, 2017). The advantage of revenue capping is that there is transparency in price estimation for the consumers. Also, there is a push for the producers and operators to increase the efficiency of the system. The challenge in case of capping of revenue is to get all the stakeholders to agree on the assessment of the level and methodology of revenue capping.

Table 13: Summary of design options for wholesale and end user pricing

DV7	Design variable options	Pro's	Con's
1	Max price for consumer	◊ Ease of implementation	◊ Difficulty in actual price discovery for the heat
2	Revenue capping for stakeholders	◊ High transparency ◊ Provides a push to increase the efficiency	◊ Difficult to get all stakeholders to agree on the assessment of level of revenue capping.

5.2 Analysis of design space

The design space presented in the previous section provides a range within which market designs of the heating sector can be observed. A monopolistic and closed heat market can be represented from a selection of design options such as Wheeling, complete public ownership of production and transportation network, no integration with network and setting a maximum price for consumers. This market design is the easiest to implement as the stakeholders are limited and ownership and operations remain with the government. However, a major drawback would be lack of competition in the market leading poor quality of service no freedom for consumers to choose suppliers.

The other end of the spectrum in the design space is a liberalized heat market with a decentralized market consisting of a public and private both type of ownership, integrated network with regulated access to third parties and revenue capping. This selection of design choices shows a market with high competition and limited involvement of the government to ensure freedom of choice and security of supply to the consumers.

5.2.1 Interdependencies between design variables

The design variables discusses in the previous section have inherent interdependencies amongst them when used in combination for a design choice. This means that some of the design options in a design variable are dependent and need careful assessment when used in combination with some other design variables only. These dependencies are as discussed below:

- ◊ A design choice comprising of 'Degree of market opening' (DV1) combination of 'Wheeling' and decentralized market (under DV2) do not make a feasible solution for any type of market. In such design variables more investigation is required before incorporating them in a design choice.
- ◊ The combination of design choice comprising of 'Public private ownership' (DV3) and 'Network regulation and tariff (DV5) presents a case in which the options depend on each other. For example, a combination of negotiated third party access with private ownership may be difficult as the private companies may not come to an agreement over network usage tariffs.

To represent the interdependency we draw from the methodology of Oei (2016) to create the interdependency matrix for the design space (Table 14). The rows and columns are the seven design variables from the design space. The cell is marked 'check' (✓) if the options of the design variable have mutual interdependency with other options of design variable.

Table 14: Interdependency between different design variables.

	DV1	DV2	DV3	DV4	DV5	DV6	DV7
DV1		✓					
DV2	✓						
DV3					✓		
DV4							
DV5			✓				
DV6							
DV7							

5.2.2 Diversity of market design choices

The diverse market designs that emerge from the design space are not only dependent on the compatibility of the design variables but also on the factors such as policy goals, path dependence and external factors, such as the endowment and macro-economic conditions (de Vries et al., 2018). The policy goals of a country may vary depending of the political scenario, ideology and geopolitics. The Danish energy policy goals include security of supply, stable and affordable energy supply. The German goal is to become the most energy efficient, environmentally friendly country and provide energy at affordable price while maintaining high level of prosperity (Liu & Ybema, 2016). Norway surprisingly lists production of oil and gas in environmentally friendly manner and become carbon neutral by 2050 as it policy goal. The UK aims at low energy bills, increased investment in energy infrastructure and mitigating climate change as its goal. The Netherlands energy policy goal is set to provide security of supply, affordable and sustainable energy (Liu & Ybema, 2016). Hence, we may see diverse types of market emerge with the same design choices.

5.3 Conclusion

In this chapter we contextualized the design variables and their options for the heat networks and markets. These were then summarized into a design space along with the pros and cons of each option. The Table 15 below summarizes the design space for heat network system.

Table 15: Design space for heat network systems.

#	Design variable	Design variable options
1	Degree of market opening	Wheeling
		Single buyer model
		Wholesale competition
		Retail competition
2	Integrated versus decentralized market	Integrated market
		Decentralized market
3	Public versus private ownership	Public ownership
		Private ownership
		Public – Private ownership
4	Network unbundling	Separate accounting
		Organizational separation
		Judicial separation
5	Network regulation and Tariff	Negotiated third part access
		Regulated third party access
6	Integration with existing networks	Integrated network
		Non- integrated network
7	Wholesale and end user pricing	Max price for consumer
		Revenue capping for stakeholders

Further, in analysis of the design space it is noted that not all design variables are compatible with each other owing to the physical, institutional or economic aspect of the network or the market. These compatibility between the variables were tabulated in a matrix format (Table 14). It was highlighted that apart from design variables other factors such as policy and politics have an impact on the design choices and market designs evolving from the design space.

6 Validation

In the previous Chapter 5 the design space for the heat network was defined. In order to validate the design space the existing heat markets are explored to see if they support the design space. This is done by exploring the Dutch, Swedish and Danish district heating sector in Section 6.1. Further, the design space is analyzed from the discussion of the experts from the industry and municipality in Section 6.2.The final results from the validation is discussed in Section 6.3.

6.1 Existing heat markets

These existing heat markets are used to validate the design space identified in the previous chapter. This is possible since the heat markets have evolved differently over time in various countries. To validation of the design space is conducted by implementing the design space for the heat network in existing heating sectors. For the purpose, we take the heating sector in Rotterdam (the Netherlands), Sweden and then Denmark.

The Swedish and Danish markets are selected as they have matured heat markets that function on different market designs. In the Swedish heating sector the prices of heat are not regulated and competition in the market decides the prices. Whereas in case of the Danish heating sector the prices are regulated for mandatory connections. These are set based on the cost plus pricing principles. (Patronene Jenni, Kaura, & Torvestad, 2017). We start first by taking an insight into the heating sector in Rotterdam region of the Netherlands.

6.1.1 Dutch district heating sector: The case of Rotterdam

District heating in Rotterdam is present from many decades. It is primary supplied by the gas fired generation sources (WBR, 2016). District heating in the Rotterdam region is mainly through the network owned and operated by Eneco in the North and the Heat company in the South.

Primary heat producer is AVR which produces heat from the waste. A total 4.5 million GJ of heat is delivered to 46,200 households in a year. The supply temperature in the network ranges from 90 ºC to 120 ºC for hot water and 50 ºC to 70 ºC for return water in the network. The capacity of the network is 105 MWth. The heat is delivered via low temperature heat network measuring over 43 kms from AVR waste incinerator (Kreijkes, 2017) (Figure 28)

The district heating market of Rotterdam is represented using the design space in Table 16. The design space shows that the heating sector in the Rotterdam is not completely liberalized as it still follows a single buyer model. The vertical unbundling is only of the producer and the distributor with no complete unbundling. The monopoly of the supplier exists and the regulation and tariffs are decided upon by the government.

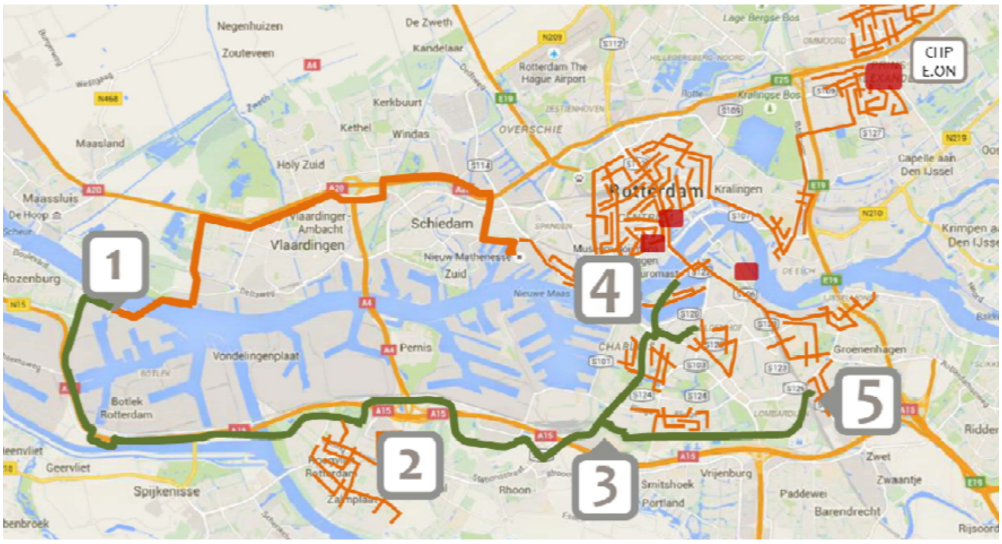

Figure 28: Heat infrastructure in Rotterdam harbor. Points 1,2,3,4 and 5 represent AVR, booster station (2 and 3), delivery point (4) and low temperature heat hub (5).Adapted from Kreijkes (2017).

The heat network starts from AVR (point1) which is the producer of heat. It then reaches to the delivery point (point 4) via booster stations (at point 2 and 3). The delivery point also supplies heat to the low temperature heat hub (at point 5) (Kreijkes, 2017) (Figure 28).

Table 16: Design Space for Rotterdam heat network system.

#	Design variable	Design option	Explanation
1	Degree of market opening	Single buyer model	There is separation between the producer and distributors. Multiple producers feed in heat to Eneco who operate and maintain the network in the north Rotterdam and WBN in the south Rotterdam.
2	Integrated versus decentralized market	Decentralized market	Long term bilateral contract between the heat producing companies and Eneco in a decentralized market.
3	Public versus private ownership	Public -Private ownership	Eneco and WBN are responsible for carrying heat from the producers to the consumers.
4	Network unbundling	None	Single firm owns the distribution and supply network.
5	Network regulation and tariff	Price capping	End user price regulation protects consumers from exploitation by heat suppliers. Tariffs are regulated by ACM that sets maximum revenue for producers and network operators. Network access conditions are not specified as there is no competition.

6	Integration with existing network	Not integrated	There is no interconnection with other network.
7	Wholesale and end user pricing	End user pricing	Pricing set under the NMDA principle

The application of the design space to the Rotterdam heating sector shows that it is a developing sector. With limited number of suppliers and a single buyer the network is open and customers do not have a freedom to choose suppliers. In this monopoly situation the price capping mechanisms prevents the consumers from exploitation by the companies.

6.1.2 Swedish district heating sector

The Swedish heat markets have developed over time in tandem with the electricity and gas markets. Historically, Sweden relied on oil-fired boilers to meet its heat demand. Post 1950's, the concern for security of supply for electricity lead to development of combined-heat-and-power (CHP) plants. The Swedish municipalities laid out extensive heat grids ensuring accessibility of heat from CHPs to consumers. In 1996, the liberalization of the electricity and natural gas sector lead to deregulation but not unbundling of the district heating sector. The development opened doors for private companies to serve the customers. By 2015, there were seven large[29] district heating companies operating along with 170 smaller heating companies owned by the municipality (Patronene Jenni et al., 2017).

The heat demand for heating in residential and service sector in 2015 was 76 TWh. Overtime, district heating emerged as the preferred alternative amongst electric heating and coal fired boilers. The graph below shows the growth in the heat supply from (biomass and municipal waste based) district heating over time in Sweden (Figure 29).

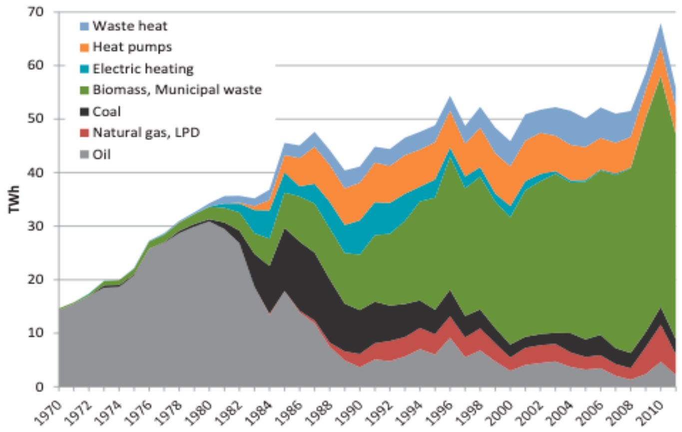

Figure 29: Change in the source of heating in Sweden. Adapted from (Patronene Jenni et al., 2017)

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[29] Networks delivering over 1 TWh of district heating

It is understood that the heat producers enjoy a monopolistic position in the Swedish heat market. The District Heating Act of 2008 ensures that the prices for connection to district heating and price determination for the heat are made available in public domain. The Act also gives freedom to the district heating companies to set the price for the heat. However, a Competition Authority can initiate investigation if it feels that there is an abuse of the policy and suppliers are charging unreasonably high prices. The liberalization and development of the heat market in the Sweden can be seen as one of the cases arising from the design space developed in this research. These are as described in Table 17 below:

Table 17: Design Space for Swedish heat network system.

#	Design variable	Design option	Explanation
1	Degree of market opening	Wholesale competition	There is a 'wholesale competition' amongst the companies. There is no regulation set for the retailers and for customers. That means the companies are not obligated to serve every customer. This has led to companies preferring large consumers but the availability of alternative and economically attractive options such as electric heating allows this market to function.
2	Integrated versus decentralized market	Decentralized market	The companies operate through bilateral contracts amongst each other and trade heat.
3	Public versus private ownership	Public -Private ownership	The network is owned by municipality owned heating companies and in some cases a collaboration with private companies. This setup ensures that heat as a public good is delivered to the consumers reliably.
4	Network unbundling	None	With almost all the grids vertically integrated the competition exists through regulated network access.
5	Network regulation and tariff	Regulated Third party access to network	Through regulated third party access the networks are made accessible to other competitors in the region. The competition between the networks develops a 'regional' price of heat which may differ across different networks.
6	Integration with existing network	Not integrated	There is no interconnection with other network.
7	Wholesale and end user pricing	Not specified	Owing to the historical development of CHP plants for electricity and heat in Sweden the price of heat is indirectly affected by the price

			of electricity. A high price for electricity (in case of cogeneration) leads to lowering the price of heat and for heat pumps leads to an increase in costs (Sköldberg & Rydén, 2014).

The Swedish market draws from the discussion on the diversity of design choice. Sweden aims to reduce its net greenhouse gas emissions to zero by 2050, and this vision guides its market regulation for district heating. The design space for the Swedish market captures the concept of 'region' and dependence on the price of electricity n heat pricing accurately. The Swedish market presents a possible outcome of design choices from the design space. Therefore, we see that the selection of design variables from the design space present as a case of Swedish heat markets.

6.1.3 Danish district heating sector

The district heating systems in Denmark started to develop in the 1920's. Similar to the Swedish energy sector Denmark invested in CHP plants to provide for the electricity and heat energy. Subsequently, the oil based CHPs evolved to solid fuels based plants. The initial fuel used for the heating was thus mainly oil. This changed with the development in pipeline technology that allowed for the possibility of supplying heat from the waste incinerators, industries for supply to district heating networks (Figure 30).

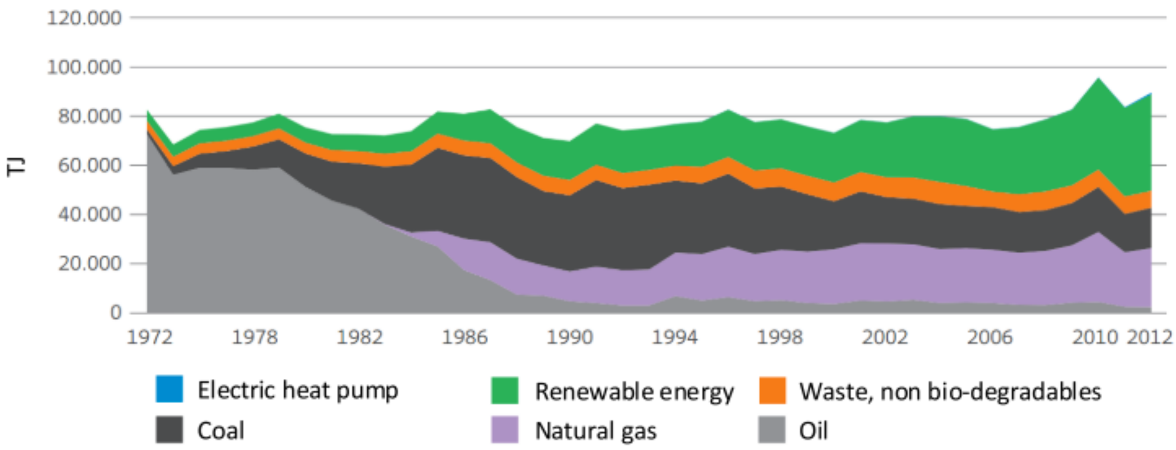

Figure 30: Change in the source of heating in Denmark. Adapted from (Patronene Jenni et al., 2017).

The total energy consumption for residential heating in Denmark was 54 TWh in 2015. Almost 63% of the citizens are supplied heat through District Heating (DH). The renewable energy (mostly biomass based) accounted for almost half of the energy input for district heating. Denmark has six main district heating areas and 400 small and medium (less than 15TWh) area. The heat is also stored for short term (up to 12 hrs) at the heating plant (Patronene Jenni et al., 2017).

The most common type of district heating system in Denmark are the small scale DH network and the large scale DH network. In small scale DH system the production and network are both owned by the local municipality or the utility cooperative. Production includes a small CHP plant along with a peak load capacity. In large scale DH networks the heat is produced by CHP and waste incineration plants owned by the municipalities or a utility cooperative. These sell the heat to the transmission companies which are usually a consortium of the municipalities. The transmission companies transmit heat to the local district heating companies which are owned by the municipalities or utility cooperatives. At present, there are over 261 network companies in Denmark. These are responsible for delivery and billing the end users (Patronene Jenni et al., 2017).

A zoning policy demarcates areas that are to be either served by DH or natural gas. The purpose of this was to setup low emission and high efficient energy systems in urban areas. Zoning helps in identifying the areas that are most viable for infrastructure development (Danish Energy Agency, 2016). The Denmark energy policy of 2012 has its target for 2030 toe provision 50% of its electricity needs from renewable energy sources. It supported the policy through feed-in premiums for electricity generation based on renewable energy systems. The decentralized CHP plants producing heat are eligible to receive a production subsidy (Patronene Jenni et al., 2017).

Table 18: Design Space for Danish heat network system.

#	Design variable	Design option	Explanation
1	Degree of market opening	Wholesale competition	Competition is introduced through geographical 'zoning' of the region. This limits the retail competition for the customers but allows for a careful infrastructure planning, optimizing network layouts
2	Integrated versus decentralized market	Decentralized market	The companies operate through bilateral contracts amongst each other and trade heat.
3	Public versus private ownership	Public -Private ownership	The network is owned by municipality or a utility cooperative. Municipality has to approve the network based on the 'zoning' requirement of the region. The ownership of the heat is with the producers which can be public or private as well. The large plant are owned by the companies while smaller plants are owned by municipalities.
4	Network unbundling	None	With almost all the grids vertically integrated the competition exists through regulated network access.
5	Network regulation and tariff	Regulated Third party access to	Regulated access and zoning allowed detailed planning of heat networks based on optimization of cost of heat delivery. Tariff regulation by

		network	Danish Energy Regulatory Agency (DERA) protects consumers from exploitative pricing.
6	Integration with existing network	Not integrated	There is no interconnection with other network.
7	Wholesale and end user pricing	Price capping	Cost plus pricing followed by the DH companies. These are benchmarked against other producers to ensure no consumer exploitation (Danish Energy Agency, 2016).

The market design of the Denmark draws from the multiple design variables of the design space. The ‘zoning’ of the heat networks in Denmark resembles the design variable ‘degree of market opening’ and vertical separation option. The impact of the renewable energy policy of Denmark also impact the development of the heat market as electricity becomes more competitive. In this case we see that different design options from the design space are able to represent the current Danish heat markets.

6.2 Expert interviews

To validate the results interview were conducted with the representative of the heat distribution company Eneco and the municipality of the Rotterdam. The discussion with the industry expert shows that there is an immediate need for a push from the policy perspective in the district heating sector. The lack of financial assistance to projects has led to slow growth of the heating networks.

The heat distribution company welcomes the possibilities of increasing the *degree of market opening* to add competition. The heat companies show willingness to open their networks for other producers under *regulated third party access* (Appendix B). However, a lack of consumers for the district heating does not allow multiple producers in a region as it becomes economically unfeasible to sustain.

The municipality presented the opinion for a more *interconnected network* in order to reduce the costs of development(Appendix B). The high costs and uncertain future of the heat market created a barrier where all interested parties are engaged in a wait-and-watch policy. However, this strategy may lead to further increase in costs as consumers may instead opt for other solution than district heating.

To sum, the industry experts agree on common point that the heat market requires competition. This corroborates to the design variables of *degree of market opening, network unbundling* and *public-private partnerships.* However, the lack of clear policy has led to high costs and risks that act as barrier to entry for the sector. Integrated networks are seen as a possible alternatives to cut costs but the ownership remains unknown in such solutions. The detailed interview discussions are attached in the Appendix B.

6.3 Conclusion

The three different heat markets are presented in the design space for validation in Section 6.1. The Dutch heating sector presented a case of developing market while the Swedish and Danish markets are more open with competition at wholesale level. The representation of these markets in the design space show that the design space represents the possible combination of design variables. The analysis of discussion with the industry expert and municipality presented in Section corroborates the ability of design space to present various heat market types based on design variables.

7 Discussion

In the previous Chapter 6 we validated the design space for the heat network. In this chapter we discuss the results, methods and learning used for the design space. We understand the relevance of the design space in terms of choices made in the process of design in the Section 7.1. Next, we discuss the methods used in the research and their relevance in designing the design space in Section 7.2.

7.1 The design space for heat network

The results of the research conclude that the similarities and differences between the characteristics of network infrastructures can be used to design markets for a similar network systems. In case of this research the design space for the heat network was carved out by drawing learnings from the study of gas, electricity, water and wastewater networks. The design space thus designed was verified by attempting to understand the currently developed and developing international heat markets. The results showed that the design space was able to represent the design choices of variables and represented the markets.

7.1.1 Relevance of the design space

In this research, the design space was arrived at by making selection amongst different types of networks, location of networks, use of models for abstraction leading to selection and rejection of design variables. We define the relevance of the design space by understanding the relevance of the selections made in the research. These are as discussed below:

Comparing different network infrastructures. As an observation, one may ask that if the basic principles of the design space for the heat market are inspired from the existing networks of gas, electricity and water markets, then in that case the structure of markets and interactions must also resemble each other. We see that it is indeed the case. The similarity in flows identified in the research advocates the presence of common characteristics across the networks (Section 3.5).

Comparing Dutch and International network systems. A point of discussion could be on the relevance of taking the Dutch electricity and gas markets and UK water and wastewater markets for drawing comparison. It is indeed possible that socio-technical and political factors leading to liberalization of markets are different across countries. Also, it is not necessary that the process of market liberalization will be similar in different countries. However, in this research we considered the case of looking at the developed markets in various network systems across region. This was done to develop a holistic design space and keep a broader perspective.

Abstraction of network characteristics. In course of the research the network characteristics were identified from the literature review and using insights from the IDEF modeling. These network characteristics were then used as hard constraints to prioritize the design variables that form the design space. It is therefore critical to discuss the extent to which the characteristics selected represent the network. It is agreed that the characteristics of each network used in the research were considered at a basic level that sufficiently represented the network. The sufficiency of network representation was established through the IDEF0 model that incorporated most of the characteristics. This said, it is definitely possible to generate a list of characteristics that present a sharper representation of network. However, with the constraint of time and resources the present level of abstraction was considered.

Using the market design framework. The research uses the framework designed by De Vries & Correlje (2008a) for design space of heat sector. It is to be noted that the framework was originally designed for restructuring of the power sector and is based on empirical observations. While assimilating the design space for the heat sector this aspect must be considered. Therefore, its use in the heat sector may include and exclude relevant characteristics of the sector itself.

Selection and rejection of design variables. The design variables considered in the design space were selected and rejected based on the hard constraints set by the critical characteristics of the heat network identified. It can be discussed that some of the characteristics that are similar between the heat network and other network may not be constraint for the same design variable. In such a case how is the coordination between the characteristics and prioritization of the design variables considered. Of the thirteen design variables we selected seven design variables as a priority and rejected the others. The reason for rejection vary from the variables being regional nature of the network to non-applicability in the case of heat networks at present. As the selection of design variables dependent on the hard constraint set by characteristics it is possible that changes in technology (such as fifth generation bi-directional heating grids etc. may lead to a change in the selected list of design variables.

Going further in the discussion, the present thesis was designed with the underlying purpose of understanding the heat energy markets. The design space presented variables that helped in clarifying the structure of heat markets in terms of technology, institution and economic aspects. It is important to know the position that can be drawn on the challenges present in the current heat markets. These are discussed under the policy implications section ahead.

7.2 Theory and methods used in research

7.2.1 Systems thinking.

In this research we used the theory of systems thinking to understand the network systems as complex socio-technical systems with multiple sub-systems and interactions. A point of discussion could be on the selection of systems thinking for the network systems. The driver for selection of the theory of systems thinking was based on the objective of the study was to draw learnings from existing network systems. In such case the best way found was to look at the different networks from the lens of systems thinking. Initially, it was challenging to identify which system to start from. Attempts were made to look at the networks from an economic perspective and from an institutional perspective. In the end the best fit was identified as taking systems perspective of the technical aspect of the network. This was easier to interpret and build on for further analysis through IDEF modeling.

7.2.2 IDEF0 modeling

The IDEF0 modeling was selected as modeling tool to present the network systems into their comprising sub-systems. A point of discussion is the selection of IDEF as modeling tool for the network systems. The requirement of the research was to understand the functionality of the various components in a network. Other modeling tools provided higher level of details whereas the IDEF0 allowed representation of the functionality in a system.

The IDEF0 modeling also produced interesting results in terms of common patterns across the network systems: flow, and storage and capacity. The flow includes flow of commodity, information and money in the network. Storage and Capacity refers to the characteristic of the network to store commodity and ability to change the flow with demand (Section 3.5). These broad categories cover most of the characteristics of the network structures. Interestingly this observation resonates with the findings by Hallack and Vazquez (2014b) who identified gas industry characterized by temporal and spatial specificity. This can lead to further discussion into how the temporal and spatial specificity appear in the network structures. This aspect of network is not covered under the scope of this research.

7.3 Results and quality of results

The overall expectation with the results was met considering the extensive task of comparing four different network infrastructures was taken up. The shortcomings rise from the same argument that the research turned out to be extensive considering the time available. The process of drawing characteristics from the four different network systems was challenging. The level of abstraction for this activity had to be fixed but that also meant that not all characteristics would be considered for drawing comparison with other networks. This was taken as a tradeoff and only main characteristics were finally selected for further use in the study.

In terms of the quality of the results generated, the design space and its validation with existing heat markets assured that the results were correct. This being said, it is also true that with more precision in selection of characteristics and design variable analysis a sharper picture of the design space is possible.

7.4 Limitations and future research

The limitations in the research arise mainly because of restriction of time and resources. The requirement lead to keeping a focus on specific sections of networks, characteristics and modeling. However these limitation also generate opportunities for further research in the domain. These are as mentioned below:

Modeling design choices: In the present research the design space formulated in the research was limited to validation by analyzing the fit of existing markets. It will be interesting to see the result of an approach in which the a number of design choices are selected to form possible markets and their validity is tested. One might see emergence of a closed heat market to a fully competitive heat market by changing design variables as ‘knobs’ of the heat network ‘system’.

Systems representation of network infrastructure. In this research the network infrastructures were represented using IDEF0 models. From this level of abstraction the characteristics of flow, storage and capacity were identified. It is possible that the network systems can be further explored in detail and more relevant insights into the similarity and differences of these systems emerge.

7.5 Conclusion

To conclude the discussion, in this research we have shown that learning from different network systems’ technical, economic and institutional characteristics design space can be formulated. We also presented that using systems thinking and IDEF modeling a functional model of network infrastructure show common patterns. This model can be further explored to generate deeper insights into networks. The design space identified for the heat network was able to reflect the existing international and local heat markets. It further corroborates the point that the network infrastructures are similar to some extent and the challenges of one network may be solved by refereeing to other networks.

8 Conclusion and Recommendation

The research question on societal problem described in Chapter 1 along with the research methods of Chapter 2 were narrowed down into a design space in Chapter 5. In this chapter we zoom out from the Chapter 5 and answer the research question asked in Chapter 1 in Section 8.1. Further, the contribution of the research is discussed in Section 8.2. In the Section 8.3, based on the results from the Chapter 3 and Chapter 5 we develop recommendations. In Section 8.4 we specify the limitations which creates opportunity for further follow-up research.

8.1 Conclusion

This research answers the overarching question of identifying characteristics of a network system defining the design space of the heat market. These characteristics are identified as the design variables in the design space (Table 19). The composition of the design space from the variables and their options is explained in Section 5.1. The design space construed above was arrived at by answering the sub-research questions on identifying similarities and differences between networks and identifying relevant design variables for the heat network.

Table 19: Design Space for the heat network

#	Design variable	Design variable options
1	Degree of market opening	Wheeling
		Single buyer model
		Wholesale competition
		Retail competition
2	Integrated versus decentralized market	Integrated market
		Decentralized market
3	Public versus private ownership	Public ownership
		Private ownership
		Public – Private ownership
4	Network unbundling	Separate accounting
		Organizational separation
		Judicial separation
5	Network regulation and Tariff	Negotiated third part access
		Regulated third party access
6	Integration with existing networks	Integrated network
		Non- integrated network
7	Wholesale and end user pricing	Max price for consumer
		Revenue capping for stakeholders

The similarities and differences between the networks was identified based on eleven main characteristics (Table 20). It is seen from the analysis that the heat network systems resemble the characteristics of water and wastewater networks and gas networks. The comparisons are covered in detail in Section 3.5.

Table 20: Similarities and differences between heat, gas, electricity, water and wastewater network systems

S.No	Characteristic	Heat N/W	Gas N/W	Electricity N/W	Water and Wastewater N/W
1	Bidirectionality of flow	✓		✓	✓
2	Flow control	✓	✓		✓
3	Speed of flow	✓	✓		✓
4	Transportation losses	✓		✓	✓
5	Network criticality	✓	✓		
6	Seasonality and density of demand	✓	✓	✓	
7	Security of supply	✓	✓	✓	✓
8	Storage	✓	✓		✓
9	Barriers to entry	✓	✓		✓
10	Geographic endowment	✓			✓
11	Commodity differentiation	✓		✓	

Based on the similarities and differences a selection of the relevant design variables for the heat network system was made (Table 21). The basis of their selection and relevance to the heat networks is explained in the Section 5.1.

Table 21: Design variables for heat network system

#	Included design variables
1	Degree of market opening
2	Integrated versus decentralized market
3	Public versus private ownership
4	Network unbundling
5	Network regulation and tariff
6	Integration with existing network
7	Wholesale and end user pricing

These variables along with their options formed the design space for the heat networks (Table 19). During the research for the design space we explored different network infrastructures using IDEF0 model to abstract characteristics. It was identified that two main sets of characteristics: a) Flow of commodity, data and money, and b) Storage and Capacity of network. The flow of commodity includes characteristics related to the flow such as bidirectionality, control, speed and transportation losses. The Storage and Capacity category include characteristics such as network criticality, seasonality and density of demand, security of supply and storage (Section 3.5).

8.2 Contribution of this research

8.2.1 Societal contribution

The research presented in this thesis developed twofold insights. First it presents a process of comparing different network infrastructures to design a new network system. The research then establishes similarity and difference between characteristics of different networks. This comparison is helpful in drawing insights for the developing heat markets through the design space. For example, the possibility of higher transaction costs in case of liberalized heat markets due to increased interaction can be drawn from the similarity in flow of information across various participants similar to electricity network systems. From this, one can derive that it would be useful to develop technology to reduce these expected transaction costs. This contributes towards providing an understanding of the heat energy transition problem discussed in Section 1.1.

Second, it proposes a design space for the heat network systems. In present scenario where there are projects such as the ‘heat roundabout’ *(Warmterotende)*, and ‘pipeline through the middle’ (*Leiding door het Midden*) the design space can provide insight into the design variables which are more critical than others in terms of impacting the network system design. For example, exploring the combination of design variable of public versus private ownership present insight into pros and cons of such a project. This helps in providing solutions for the problem of ownership and integrated or decentralized network as discussed in Section 1.3.

8.2.2 Scientific contribution

In terms of scientific contribution the methods and theory used in context of formulation of the design space presents itself as a novel contribution. The theory of systems thinking was applied to the network structures of gas, electricity, water and wastewater networks to develop an IDEF model. As a result of application of this model to the network systems, characteristics that define a network system were identified (Section 3.5). Also, modeling of network infrastructures as sub-systems with interconnections and flows is an extension to the theory of systems thinking. The IDEF models for the gas, electricity, water and wastewater network systems provided a new perspective to look at the network infrastructure systems. This abstraction at functional level will help in identifying patterns and connections while designing a new network system.

The design space for the heat network along with the interdependency matrix and diversity of market design choices presents as an addition to the framework of market design for electricity markets by Correljé and Vries (2008b). The validation through existing markets show that the design space encompasses the past design choices made for those markets and therefore holds valid.

8.2.3 Further research

The present research limits itself to the development of a design space providing a set of design variables for the heat market. Based on the results, further research can be carried out by selecting a combination of design options from the design variables to arrive at various heat markets. These can then be modeled and tested quantitatively for completeness and used to generate insights. The research also opens a possibility to used IDEF modeling technique to unpack and understand the network infrastructures in detail.

8.3 Recommendations

The Netherlands faces the problem of phasing out natural gas and need for designing an alternative for the heating network. The following recommendations are for the Ministry of Economic Affairs and Climate Policy as they are the main responsible stakeholder for the transition.

8.3.1 Recommendations for MEA

Decentralized development of heat networks. The choice of market opening for the heat sector in tandem with region based zoning can provide a design choice for regional heat markets with differentiated prices. This is more of a decentralized choice that acknowledges the regional character of heat similar to other international heat markets. Based on separate zones different sources of heat production would supply to local demands in a zone.

Distributed ownership of heat networks. In case of an integrated network plans such as the '*heat roundabout' (Warmterotende)*, and '*pipeline through the middle*' (*Leiding door het Midden*) the ownership can be distributed as public, private and public-private across the network. The ownership of the network at the national level could be public, at regional levels a utility cooperative and at neighborhood level private entity. It would ensure the security of supply of the heat and ensure that the quality of service is kept high.

Compatibility with water and wastewater networks. The comparability between the network system of heat and water and wastewater supply network throws open a possibility of integration of the two networks. The concept of extracting heat from the sewage and cold from water supply can be further researched upon. With the development of fifth generation of district heating networks and efficient housing the energy extraction from water and wastewater supply network would be an effective solution.

8.3.2 Recommendations for technology firms

Focus on information management. The flow of information is an important part of the heat network systems. The upcoming shift to a district heating network and an open heat market is expected to create an increase in the flow of data in the network. The similarity of the information flow of the heat network with that of other network systems showed that it is likely that the use of heat meters will increase in future.

a. Technology firms can invest in research on the technical solutions for collection of data from the users (via heat meters), profile generation, demand forecasting would be required.
b. Technology firms can develop solutions for the energy companies and customers by providing tools for management and analysis of their heat consumption data

Focus on asset management. The increase in participation of stakeholders in the heat market would create possibilities of assets and customers changing ownership amongst wholesaler and retail supplier of heat in the future markets.

a. Technology firms with their experience in technology such as blockchain and smart contracts, can develop a business case in these emerging heat markets. The ownership of the capital assets (like grids) and consumers can be shared or transferred through smart contracts leading to a reduction in administrative transaction costs and also making the heat networks easier to access for other actors.

Harnessing diverse knowledge pool. The comparability between the different network systems presents the insight that different sectoral teams within firms located globally can collaborate and work together to develop new solutions and products for emerging problems in a sector (such as heat sector). Therefore, cross domain and international teams can be formed that harness their sectoral expertise and bring in their different perspectives together.

Collaborations with technology companies. The technical expertise in the development of solutions for the heat markets can be conceived inhouse. Firms can also collaborate with other engineering companies. An alternative way is to look at acquiring small companies and star-ups that work on the state of the art heat network technology.

Reflection

It was around July 2018, that I had decided in my mind that I would be writing my thesis research in the area of heating sector for the Netherlands. The motivation came from the expectation of implementing learnings from the first year of Masters studies and a drive to ‘solve’ a societal problem. By start of February 2019, I was, as per my understanding very specific in selecting the problem of ‘pricing of heat in Netherlands’ as a thesis research topic. It was with this topic that I had first few meetings with my supervisors, Dr. Ir. Rob and Dr. Aad, who was prodding me to rethink the scope of the problem. Initially, this was unsettling as I believed that the scope was very well narrowed down and precise. But, it took me a month of reading, and meetings to realize the enormity of the heat problem. I realized that what I had in mind was a topic of elaborate research and a Master thesis research of size month would not be able to do justice to it. Realizing that after the initial ping-ponging of ideas, I narrowed down the research to ‘design space’ of the heating sector.

I believe that limiting the scope made me feel that I can now go deeper into some other part of the research. That happened when I selected four network infrastructure systems of Gas, Electricity, Heat, Water and Wastewater to compare. I didn’t realize it then, but this made the research ‘too huge’ of a task to be researched in detail. As a result of this selection I had to read up on a vast range of literature, which became a challenge as it was difficult to stop myself from going in further details of the networks. It was here that discussions with Dr. Rob helped me keep put a check on the readings and focus further on the analysis part of the research.

While conducting the analysis of the networks and attempting to draw similarities and differences I faced difficulty in structuring the comparison of the networks that comprised of various characteristics. Here, I found the discussion with Dr. Ir. Rob and Mr. Sjors helpful. Their suggestions with IDEF model was much needed as it was this phase where I felt I was spending more time in searching. Another challenge was writing down the research in a concise and clear form. With my past academic and professional experiences in social sciences and development sector it took sincere rewriting work for conclusions and recommendations. At the completion of this thesis, I find that one of my biggest learning is being straightforward and direct in putting across the point.

Overall, I found the most challenging aspect of the research being the task of setting the boundaries at each stage starting from problem definition, method selection, analysis, conclusion, recommendation and also discussions. Through the journey of this research I take away the learning that novelty of a challenge and can be overwhelming and one must be take a practical view to define solutions.

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Appendix A: Thesis Research Paper

Using IDEF Functional Modeling to Identify Characteristics of Network Infrastructures

A Case Study in Electricity, Gas and Water Supply Networks

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Abstract: The design of network infrastructures is seen a complex systems problem. The process for the design of these systems has varied based on the technical or market oriented perspective of the researcher. Recent developments in comprehensive framework aligning both the technical and institutional perspective tried to remove the tradeoffs from selecting a single approach. Some approaches have drawn from other markets and followed other sectors to design the markets. In this paper we extend the IDEF0 (a functional modeling technique) to different network systems to identify fundamental characteristics that the different networks share. This insight is expected to provide a case for IDEF0 application in identifying design variables across the network systems to define a design space for new neterok infrastructures.

Keywords: IDEF, functional modelling, network, infrastructure, electricity network, gas network, water and wastewater network.

I. INTRODUCTION

The network infrastructures are defined as complex socio-technical systems that are used for transportation of people and goods. The complexity arises from the combined effect of the social economic and physical complexity of the infrastructure systems (Herder et al., 2008). Examples of network infrastructures include energy networks such as electricity and gas, and water supply networks.

The approach for the design of the energy infrastructure has largely remained scattered. The complexity of this systems creates a dilemma weather to design the system from a technical perspective and keep the goals or reliability and robustness as primal, or take a market oriented perspective and focus on efficient and effective distribution of goods and services (Scholten & Künneke, 2016). However, both the perspective lead to an inefficient design as they overlook the other aspect of infrastructure design.

Scholten and Künneke (2016) presented a comprehensive design framework that relates design variables on the technical and economical dimensions to design a network infrastructure. Rinaldi (2001) suggested a similar interdependency within the infrastructures and amongst the different infrastructures as well. Energy infrastructures across the world have depended on learning from each other for liberalization of their markets and network infrastructures. The systematic unbundling of the European electricity markets and network access was initiated through the EU directives. The gas sector liberalization soon followed the electricity market path (Newbery, 2002). These developments shows that there are inherent systemic similarity and existence of characteristics that are common across the network infrastructures. Further, these can be used to identify design variables for developing markets for new network infrastructures.

The challenge is to study the different network infrastructures through a common language so that the abstracted components are comparable and inferences can be drawn. The IDEF0 modelling technique is used for a structured analysis and design of systems (Presley & Liles, 1998). In this paper, we present a novel application of the IDEF0 technique to first, model the network infrastructures of electricity, gas and water supply networks and then analyze the models to identify characteristics common across the networks. For the purpose of this research the Dutch electricity and gas networks and UK's water supply and wastewater network are considered.

II. HISTORY AND BACKGROUND OF IDEF0

IDEF – A Systematic Modelling Technique

In 1970's, the U.S. Integrated Computer Aided Manufacturing (ICAM) unit sought to increase the productivity through better analysis and communication technique. The IDEF (Integrated DEFinition language) technique thus developed and a variation of the technique that focused on the 'functional model' of a system with inputs, outputs, activities and control mechanisms was defined as the IDEF0 (FIPS PUBS, 1981). IDEF0 is a graphical modelling language with semantics and syntax.

The main elements of the IDEF0 include: inputs represented by the arrows flowing into the left hand side and outputs represented by arrows flowing out the right hand side of an activity box; the activity (or process) is represented by the boxes themselves; the arrows flowing into the top portion of the box represent constraints or controls on the activities; and the final element represented by arrows flowing into the bottom of the activity box are the mechanisms that carries out the activity.

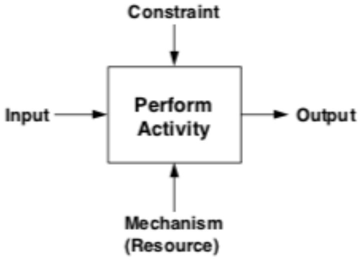

Figure 1: A sample A-0 level IDEF0 representation.

The IDEF0 representation can have multiple level of granularity. Each level of IDEF0 depicts a detailed information about the subsystem, input-output, mechanisms and constraints. In the next section we proceed further to apply IDEF0 technique to electricity, gas and water and wastewater networks as case study.

III. Case Studies

Electricity network

The electricity network includes power production, transmission, distribution and consumption. All the activities are modelled into the boxes with separate inputs and outputs. The input for production activity are the primary energy source and revenue. High voltage power is generated as the output and fed directly to the transmission lines and send to the interconnectors. The voltage of the electricity decreases from as it goes from transmission lines upstream to consumers downstream. The high voltage power contracted in power exchange and bilateral market from the producers is delivered to large consumers. Smaller consumer contract power from the retailers through retail markets.

The consumers generate profiles that are collectively sent as balance program responsibility data by the Balance Responsible Parties (BRPs) to the distributors. The BRP at the distributor end then shares the information received as energy schedule with the Transmission Systems Operator (TSO) and the producers. The consumption data is shared by the consumers with their balance responsible parties, who shared the energy schedule with the Tennet (TSO). The TSO compiles the energy schedules into an energy program and shares it with the producers and sets a constraint on increasing or decreasing the production for the power distributors.

The end consumers pay for the energy, connection and capacity costs to the BRPs. The operator Tennet is allowed to make revenues comprising of their operating cost and the allowed cost of capital only. The revenue follows the same track and reaches the TSO through the

BRP. Throughout the entire process the network system is regulated by the market regulator (ACM) setup under the EU Electricity directives and the Electricity Act.

The Figure 2 shows an IDEF0 model of the electricity network. The diagram brings out features such as the flow of electricity, information and money. As it is not possible to store electricity efficiently, the lack of storage results in mechanisms such as balancing mechanisms and capacity allocation being applied in power transmission.

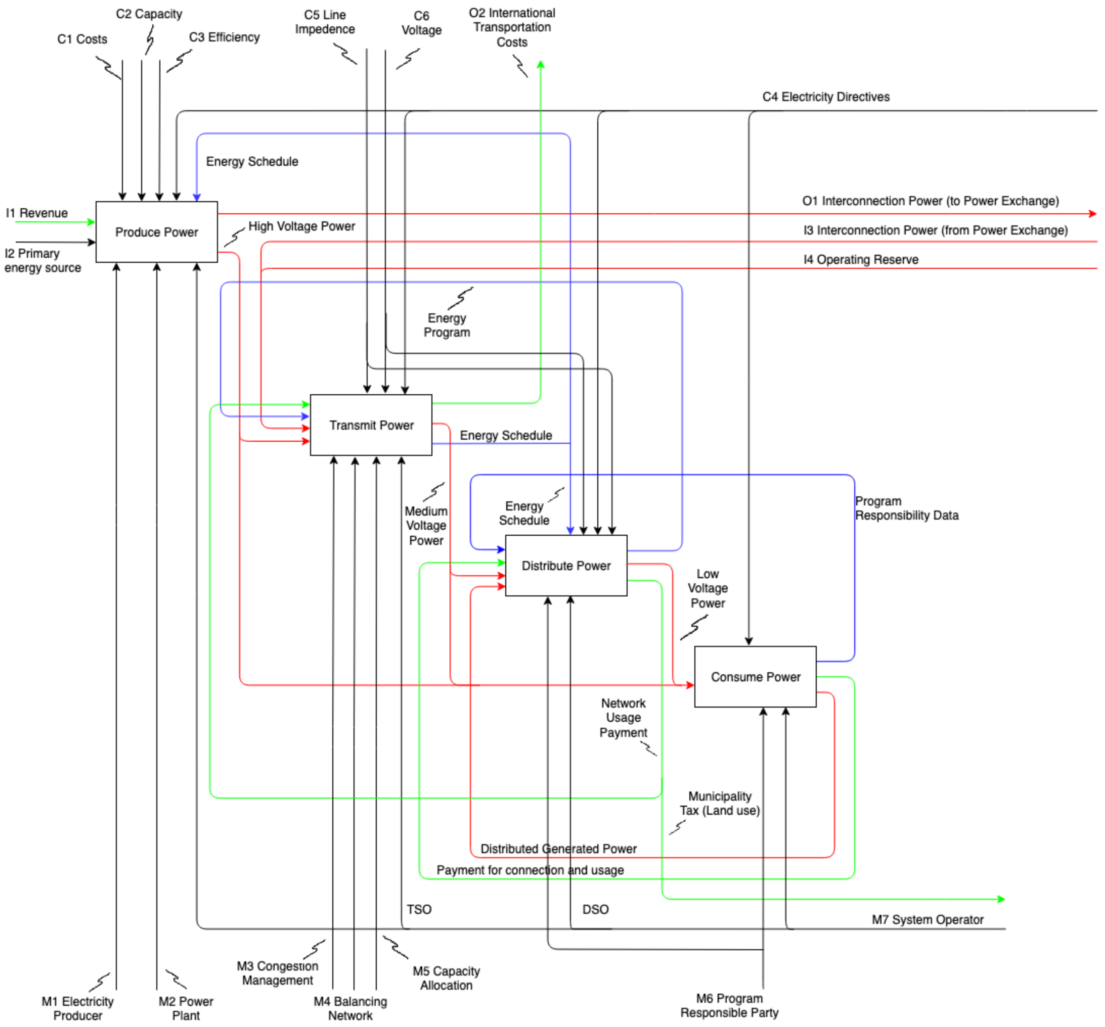

Figure 2: IDEF0 model for electricity network system

Gas network

The gas pipelines network along with components move the natural gas in a reliable, efficient and effective manner. These pipelines are designed keeping in mind the impact of critical factors (such as temperature, pressure on the gas flow) emerging from the physical and chemical characteristics of the gas.

The activities in the gas network system include production, transportation, storage, distribution and consumption. At the production level, a coalition of the partnership (NAM or Nederlandse Aardolie Maatschappij) of the Dutch government (represented by EBN, ‘Energie Beheer Nederland), Exxon and Shell owns the exploration and production right of the natural gas in the Groningen and small fields. The TSO is responsible for the network safety, reliability, operations, transport capacity, maintenance of connection with national and international networks, balancing the network and ensuring supply of gas for temperatures as low as -17 ºC.

The DSOs are responsible for ensuring the efficient, safe and secure delivery of gas through the distribution network. The shippers can access the gas network operated by the GTS by booking transport capacity at entry and exit points. There are eight LDC’s in the Netherlands who own their separate network and are connected to the GTS’s national grid. The multiple shippers are allowed to contract capacity in the network to transport the gas to its destination.

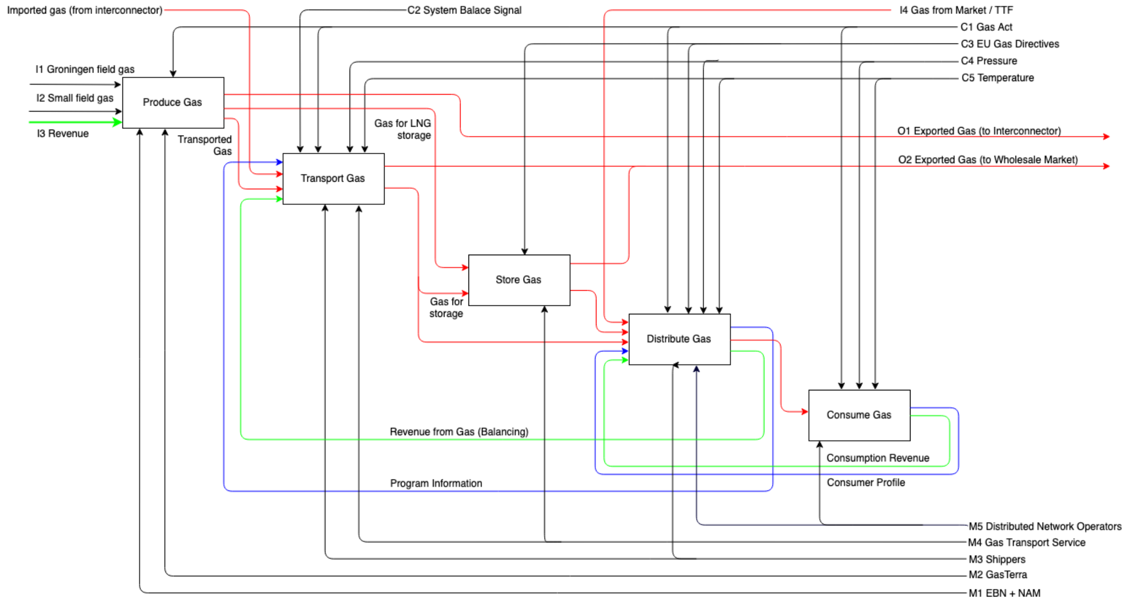

Figure 3: IDEF0 model for gas network system

We can observe from the IDEF0 representation Figure 3 that the gas flows are complex between the transporters and distributers. The gas flows through markets and storage units add to the input of distributers under the flexibility mechanism. Since the storage is possible for gas it becomes a separate main activity in the value chain of the gas network. The data of consumption is shared by the customers to the distributors as a ‘consumer profile’. The distributors combine all the different consumer profiles to generate a ‘program information’ for the transporter based on which the balance of the transportations pipeline network is maintained.

The ACM also sets the tariff for all system operators every year. Based on these tariff GTS charges for tasks such as transportation, balancing, quality conversion, connection and maintaining existing connections. The charged by the DSOs are based on the annual consumption (fixed charge) and the capacity used (European Commission, 2015). The base revenue for GTS is set as the estimated cost level to ensure efficiency gains for the customers. For the DSO's the revenues are based on the average costs of the system operator itself. The consumers pay for the transportation of gas, contract capacity, periodic connection fee and administration costs (Enexis Netbeheer, 2019).

Water and wastewater network

The water and wastewater network differs from the other networks in the context of the flow of water which is circular. At present there are around 12 water and sewerage companies and 9 water only companies operating across the UK. The regulation of the operation of these companies is done by Ofwat, Drinking Water Inspectorate and Environmental Agency. The wholesaler owns the network and provides water and sewerage service to the customers in the region. The retailers are responsible for providing value added services such as meter readings, grievance redressal etc. The wholesaler is paid for by the retailer who in turn sends the bills to the consumer.

The transactional exchange between the wholesaler and the retailer is managed by a market operator. In UK, the Market Operator Services Limited (MOSL) collects the tariff information from the wholesaler and meter readings from the retailers to calculate the daily charges and aggregates them in a monthly invoice for retailers.

If a customer switches their retailer then the connection information of the customer is updated by MOSL with new retailer thereby making choosing of retailer an option and introducing retail competition. Introduction of a MOSL retail market has led to lower bills, increased efficiency of water supply and improved customer services (OFWAT, 2018)

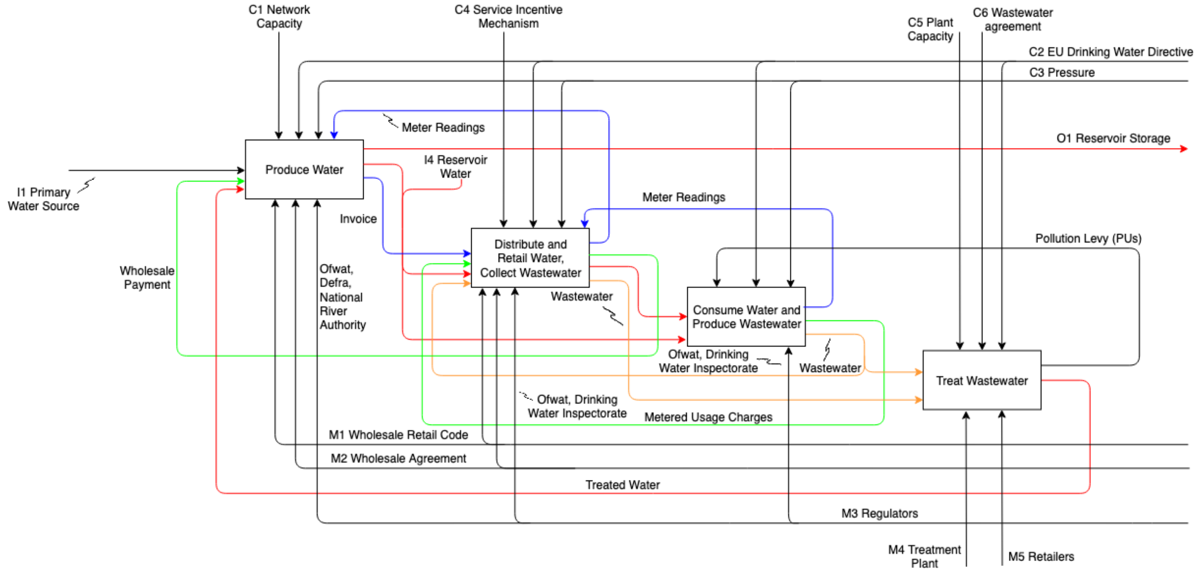

Figure 4: IDEF0 model for water and wastewater network system

IV. RESULTS

Modelling the different network structures as a system of subsystem in IDEF the similarities and differences between the two energy network and a water network becomes clear. While there are many physical, institutional and economic factor that may cause these variations in the network systems we see that three main characteristics: *flow*, *storage* and *capacity* emerge. These are explained in detail as below:

a) All three networks have a similarity in *flow* of commodity, data, and money.

Amongst the different networks we see three different type of flows. These are represented by arrows marked in red, blue and green for flow of commodity, data and revenue respectively. The flow of commodity is from upstream to downstream. That is from the point of generation to the consumption. The exception is the case of electricity where the consumers generate electricity that flow upstream to the distribution network. The flow of data and money is in reverse direction and goes from consumers to the producers via distributors and suppliers. This information flow feeds in the system as a constraint and determines the production, transmission and distribution of the commodity. The revenue feeds in the system as an input at different sub-system level.

b) The differences between network emerge from storage and capacity.

Emerging from the physical characteristics of the commodity, the possibility of storage and transport capacity differentiates the three different networks. This is seen from the IDEF model where the gas and water networks have storage as a part of the activity. In the gas network external and internal storage (linepack) is possible due to the compressibility of the natural gas. In case of water network the storage is in the form of external reservoirs. The capacity of the transport pipeline network for the gas and water network can be adjusted based on the temperature and pressure differentials. Various balancing mechanism and capacity mechanisms are therefore made a part of the gas and water supply network. In case of electricity network neither storage not capacity can be controlled. lack of possibility to store energy made other mechanisms such as balancing mechanism and capacity storage of the network.

V. FINDINGS AND CONCLUSION

The finding from the IDEF modelling are in sync with the other researches that explored the critical network infrastructures. Vazquez and Hallack (2012) remark that the spatial and temporal specificity characterize the network assets. Matuschke (2014) and Carainic (2012) studied the importance of flow in a network and identified flow as a constraint in the network design. Samsatli et al. (2015) explored the emergence of storage as characteristic from the spatial temporal variability in an energy system. In terms of capacity its importance in transport network to provide flexibility in the network has been discussed by network operators Gasunie and TenneT (2019).

Drawing a comparable systems model between the different network systems allowed the possibilities of learning from the market of a sector and apply to another similar markets. Using more complex IDEF models such as IDEF1 and IDEF2 a more exhaustive and systematic study of the network systems can be conducted. In the context of this research drawing from the results and findings we conclude the following for design of energy infrastructure using IDEF modelling:

i. IDEF0 modelling language provides a functional model that can abstract the temporal and spatial characteristics of the network systems.
ii. The characteristics identified from the IDEF0 modelling of energy and water network systems can be further categorized into variables that constrain the network characteristics.

These variables can be used as constraints for design variables in the design space of markets for novel infrastructure systems comparable to the existing network systems.

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Appendix B: Expert Interviews

Interview with Lievense

Interviewee: Mr. Sanjay Ganeshan, High Voltage Engineer

Date: 28th April, 2019

Purpose: Technical and economic insights into the electricity networks in the Netherlands.

Summary of discussion

A brief introduction into the purpose, scope and current progress on the research was shared with Mr. Sanjay to the start of the discussion. Mr. Sanjay started with a brief explanation of flow of power in the electricity network. He shared that the transmission of energy flows from the suppliers, TenneT (TSO), DSO and to customers. He also mentioned that with the onset of affordable generation technologies consumers are now becoming prosumers, which is a challenge in the existing electricity network structure.

Electricity flow. Mr. Sanjay shared that by design the electricity network is optimized to allow one directional flow. This is due to the fact that in case of a strong back surge of electricity could damage critical assets such as transformers and power lines. He also mentions that due to large interconnectedness of the electricity network any failure at one point could escalate into cascading meltdown leading to blackout. He cites the example of failure triggered by a grid failing in Italy in 2003. Mr. Sanjay further shares that to prevent this circuit breaker are put in to restrict backward flow. However, with the onset of prosumers, there is a need to find alternative solutions to this design.

Network Topology. Going further into the discussion Mr. Sanjay touched upon the topic of electricity network topology and showed it using the ‘*Google Earth Pro*’ and ‘*HoogspanningsNet’* plugin. He explained that the network operator puts in a radial network in the regions where there are a) critical assets, b) need for reliability. He explains further that in electricity network systems the transmission assets are critical with long lifetime and therefore there is a ring topology in HV lines and more distributed topology in LV networks. Here, he brings in the concept of n-1 redundancy and the ability of ring topology to provide that level of availability. While on the topic of availability, a question was asked on using batteries to store electricity. Mr. Sanjay believes that at present the electricity storage is not economical option. He shares that the storage to size factor of the battery is low and therefore less efficient.

Transmission network. On the topic of transmission lines and their capacity, Mr Sanjay says that transmission operators avoid over loading the capacity of the transmission lines as it would lead to deterioration of the line, which is expensive and a critical asset. In such cases the operator prefers to increase capacity of the transmission line by adding a new transmission cable instead. He shares that the electric systems follow a ‘bathtub’ curve representing that the number of failures are high in a new equipment life time and then increases exponentially at the end of its life. Loading the lines less than the rated capacity increase the time for the equipment.

Mr. Sanjay shared that the electricity network has different voltages across different points in order to minimize the losses. He explains that this is the main reason why HV lines are used for transmission over long distances and LV lines for local distribution. He goes further and shares that the customers pay for the energy received at their doorstep and not for the energy lost in the process of distribution. Mr Sanjay shares that while the TenneT is responsible for ensuring capacity (in GW or MW), the DSO contract the customers on basis of energy (MWh). This he says is due to the difference in the responsibility of each actor. Which TenneT as TSO with its HV transmission infrastructure ensures availability, DSO’s ensure the accurate demand is shared with the TSO. The DSO’s therefore have an inherent interest in accurately estimating the demand of the consumers so that they do not buy energy from the spot market at peak price which is expensive. Going further, Mr. Sanjay shares that as there are contracts between these parties any failure to meet the promised demand would lead to financial penalties for the generators and DSOs.

In the end, Mr. Sanjay stressed on the fact that the electricity network is highly dependent on the balance of the demand and supply of the load and power. The network infrastructure and markets are aligned to ensure that this balance is maintained in a reliable manner.

Interview with Eneco

Interviewee: Mr. Roelof Reineman, District Heating Expert

Date: 29th April, 2019

Purpose: Technical and economic insights into the District Heating network in North Rotterdam and the Netherlands.

Summary of discussion:

The discussion started with a brief introduction about the purpose and scope of the thesis research to Mr. Roelof. After the introduction Mr. Roelof informed that it would be a good idea to look at the USEF framework that provides a generic framework for energy markets.

Heat network. The first area of discussion was on understanding how does the network system of (district) heat network differ from that of electricity networks. Mr. Roelof informs that there is difference in the technical characteristics of electricity and heat as commodities. While the electricity network acts as a copperplate (with instantaneous flow), the heat does not have immediate flow. He points out that this factor also leads to a difference of scale. The electricity networks are large and interconnected but the heat networks are more localized in nature.

Critical measurement for Heat. On the question of what is the critical measurement parameter for a heat network, Mr. Roelof replies that ‘pressure (differential)’ is an important measure in the heat network. He explained with an example that when a consumer consumes heat (for example through hot water shower), then this outflow of hot water leads to a drop in temperature in the local heat exchanger which in turn results in the drop of pressure of the supply from distribution point. This pressure drop results in an increased flow rate from the source and the flow is maintained in the heat network.

Network layout. Mr. Roelof adds that this transportation of heat (from source to consumer) takes time and is unlike the ‘copperplate’ of electricity network. He mentions that this characteristic feature of heat flow also leads to the way the network is laid out. He explains by stating that from a heat source to the distribution point there is a single large pipeline and from a distributor to consumers there are multiple radial networks. This, he states is because in a state of sudden failure from source the heat will not be cut-off immediately for customer as the hot water remains in the network (through radial connections at local level) and no effect will be felt by customers in the end (if the temperature drops by few degrees for short period).

Economic aspects. Next, the questions were asked on the economic aspects of the heat network. On the topic of how the payments for heat are made, Mr. Roelof mentions the ‘Heat Law’ that caps the maximum price a customer could be charged by the heat supplier. In terms of relation between the source and distributor (in case of Rotterdam North) there is no defined ‘market’ as such and Eneco has contract with three suppliers. He mentions that with a lead time of few days Eneco provides demand estimates and contracts heat from the suppliers. Mr. Roelof says that in future a heat market may emerge if there are sufficient number of consumers for district heating, which is not at present. But, he also brings out the point that as most of the suppliers of heat are also engaged in electricity production which works on spot markets, then this inherently pushes the suppliers to ensure a similar 'market-like' contract for heat in order to reduce their own variability of supply.

Storage. Looking at the present trend in electricity market where 'flexibility' through storage is pitched as a solution, same question was asked to Mr. Roelof with respect to heat network. Mr. Roelof replied that though strides are being made in the electricity storage and prices of batteries have come lower, the same is not true for heat energy storage. He mentions that there are on-going research in storing heat in salts but it is still in early stages. On being asked if it is anyhow possible to store the heat energy within the transport network like that for the gas network, Mr. Roelof replies that due to the nature of the water the only way more heat can be stored is by allowing the temperature to rise. However, he mentions a critical point that if the temperature of network keeps increasing and finally matches that of the source then there would be no further flow of heat energy from source and it would be needed to switch off. He goes on to add that the current method of relaying demand estimation in advance to the distributor and in-turn to the supplier is a better way forward to ensure reliability of service.

Third party access. In the end, a question was asked if Eneco allows a third party access to its district heating network and charges the suppliers. Mr. Roelof replied that it is not the case yet and also not feasible in present scenario where there are very few customers and the cost of addition of new supplier will make their production and supply economically unfeasible unless they bring in new consumers along with them.

Interview with BBL Company

Interviewee: Mr. J.T. (Jelle) Krouwel, Technical Consultant

Date: 22$^{\text{nd}}$ May, 2019

Purpose: Discussion on the gas network systems

The interview with Mr. J.T. (Jelle) Krouwel was conducted at the Gasunie office in Groningen province. The interview was conducted with a structured methodology wherein Mr. Krouwel was first briefed about the thesis research its objectives and then questions were asked on various areas of the gas network systems in the interview. A summary of the discussion is presented below.

Gas pipeline network. The discussion started with Mr. Krouwel sharing details about the technical characteristics of the gas pipeline systems. He shared that the critical aspects of the gas pipeline network systems include the pressure reduction connectors, compression stations and heaters. He explained their importance by highlighting the fact that the relationship between the pressure and the distance travelled by gas resembles a decreasing step function with each connection point in the pipeline network acting as the edge of the step. Mr. Krouwel further states that the pressure at the extraction point of the natural gas goes as high as 300 bars, while the pressure at the consumer end is near about 0.1 bars. The pressure drops between different sections of transportation and distribution pipelines are maintained by a system of two valves. Mr. Krouwel explains that as the gas travels in the pipeline it loses heat and hydrates are formed. This hydrate formation leads to a loss in the quantity of the gas and therefore, to prevent this hydrate formation the gas is heated by the heaters present in the stations across the network.

Redundancy. Mr. Krouwel shared that for the security of supply for the consumers, the gas network maintains high level of redundancy. The gas network from the production source to the distributors consists of multiple alternative pipelines resembling an interconnected tree structure. This is to ensure that in case of disruptions due to scheduled maintenance or accidental outage there is no disruption of gas supply from the source to the distributors in the network.

Bidirectionality. On the question of bidirectionality, Mr. Krouwel says that it is difficult to implement bidirectionality in the network at present as the present system is a top-down gas distribution system and there are problems in maintaining quality of the gas in the network. However, he believes that with onset of green gas and interaction with other energy grids this may change in future.

Quality. On the topic of transfer of gas from Gasunie to distributors such as *Stedin*, Mr. Krouwel says that the transactions are done based on grid connection agreement and other contracts. Specifically, the grid connection agreement includes parameters such as the pressure, temperature, oxygen level and water vapor content in the gas. Both the parties ensure that the quality of gas meets the agreed upon connection agreement.

Tariffs. Mr. Krouwel explained that the process of tariff calculation for the gas network for the shippers was based on entry and exit point. The tariffs for each pair of entry and exit points are set and calculated in €/KWh/yr. For the customers, Mr. Krouwel says that the major component of cost is the taxes and price of gas as commodity. The share of distribution and transmission costs are low compared to these. Therefore, Mr. Krouwel opines that market interventions such as unbundling must be carefully evaluated for their economic relevance.

Markets. Discussing about the gas markets and their development in the future, Mr. Krouwel shared that the volatility of the gas markets is expected to be low compared to the electricity markets. This, he shares is because of the main usage of gas in residential heating purposes. He explains with an example that if it is cold in the Netherlands, then it will be cold in the neighboring countries. Therefore if the demand is high in the Netherlands it will also be high in the neighboring countries. In such cases, he raises a question on the feasibility of designing a market for the international trade.

Future of natural gas. Mr. Krouwel shares that with the plans of the government to move away from natural gas there are other renewable alternatives emerging for residential heating. In his opinion, Mr. Krouwel believes that Geothermal would provide the baseload requirement of the consumers, followed by seasonal storage, day storage and Liquified Natural Gas for meeting the short term peak requirements. On the question of present situation of Geothermal energy, Mr. Krouwel agrees that exploration and supply is an expensive process and further clarity from the policy side is needed. He believes that it takes decades to shift from one type of energy to other alternative and expects the same timescale for the shift from gas to renewable sources.

Interview with Municipality of Rotterdam

Interviewee: Mr. Wil Kovacs, Manager Subsurface Rotterdam

Date: 7^{th} July, 2019

Purpose: Validation of design space for the heat networks.

Summary of discussion

The discussion started with a brief introduction about the thesis research topic and the results of the design space. Mr. Kovacs started by sharing that at the moment all option for heating are open for the municipality of Rotterdam, including electric and solar thermal heating. He mentions that having a standalone district heating is not an economically viable solution and therefore there are options to interconnect the different networks. On the question of ownership of such a network, Mr. Kovacs opines that it has to be a mix of ownership with the government playing the role of facilitator supporting the development.

Current scenario. On the topic of present scenario Mr. Kovacs shares that it seems that everyone is taking a wait-and-watch strategy as the economic risks of entering into the district heating network are too high. Mr. Kovacs also shared that the municipality is taking strides in developing the heating ‘backbone’ from Rotterdam to supply heat to nearby areas. He mentions that the while the work for a north and south heat connection is completed there is progress in connecting to the east and west sides.

Costs of transition. Speaking on the topic of who pays for the heating network development Mr. Kovacs says that the burden will ultimately fall on to the customers. If the private companies develop the network then the costs will be added to the customers and in case the government builds the network then the consumers pay through taxes. Summarizing, Mr. Kovacs says that energy transition is expensive.

Future alternatives. Going forward, Mr. Kovacs asserts that solution has to be integrating different activities to reduce the cost of development. Waiting will further lead to an increase in costs as the new constructions will not wait for district heating networks. The option for electric heating is still expensive for existing households and the houses themselves are not suitable for electric heating.

Appendix C: IDEF0 Models

IDEF0 Model for Gas Network Systems

The IDEF0 model of the gas network system consists of five main sub-systems that interact with each other. These are Produce Gas, Transport Gas, Store Gas, Distribute Gas and Consume Gas.

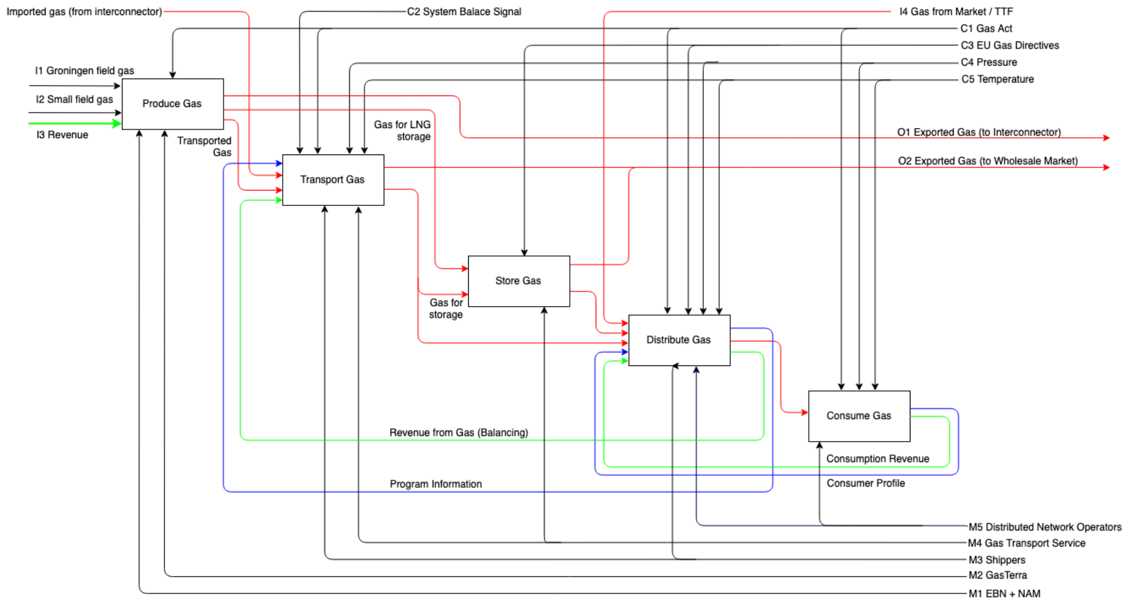


Figure 1: IDEF0 model for gas network system

Produce Gas. In the '*Produce Gas*' sub-system the production step is represented in the model. The natural gas extracted from the gas fields through processes that are regulated under the Dutch Gas Act. Therefore, the input for this sub-system includes various sources of natural gas extraction (that is Groningen Gas fields and offshore Gas fields), mechanism includes the gas producing companies (NAM, EBN, GasTerra and others), control includes the Dutch Gas Act and output as gas that is exported and transported into the gas network.

Transport Gas. The *'Transport Gas'* sub-system includes the transportation of gas from the production unit to the distribution and storage points. The inputs for this sub-system include gas imported from the interconnector, gas produced (by the '*Produce Gas*' sub-system), and program information and revenue generated by the gas balancing (from the *'Distribute Gas'* sub-system). The mechanisms include the shippers and the Gas Transport Service, whereas the controls include the System Balance Signal, regulations such as the Dutch Gas Act, and physical control through Pressure and Temperature measures. The outputs of this sub-system are gas exported to the wholesale market, gas sent for storage (to the 'Store Gas' sub-system) and gas sent for distribution (to the 'Distribute Gas' sub-system).

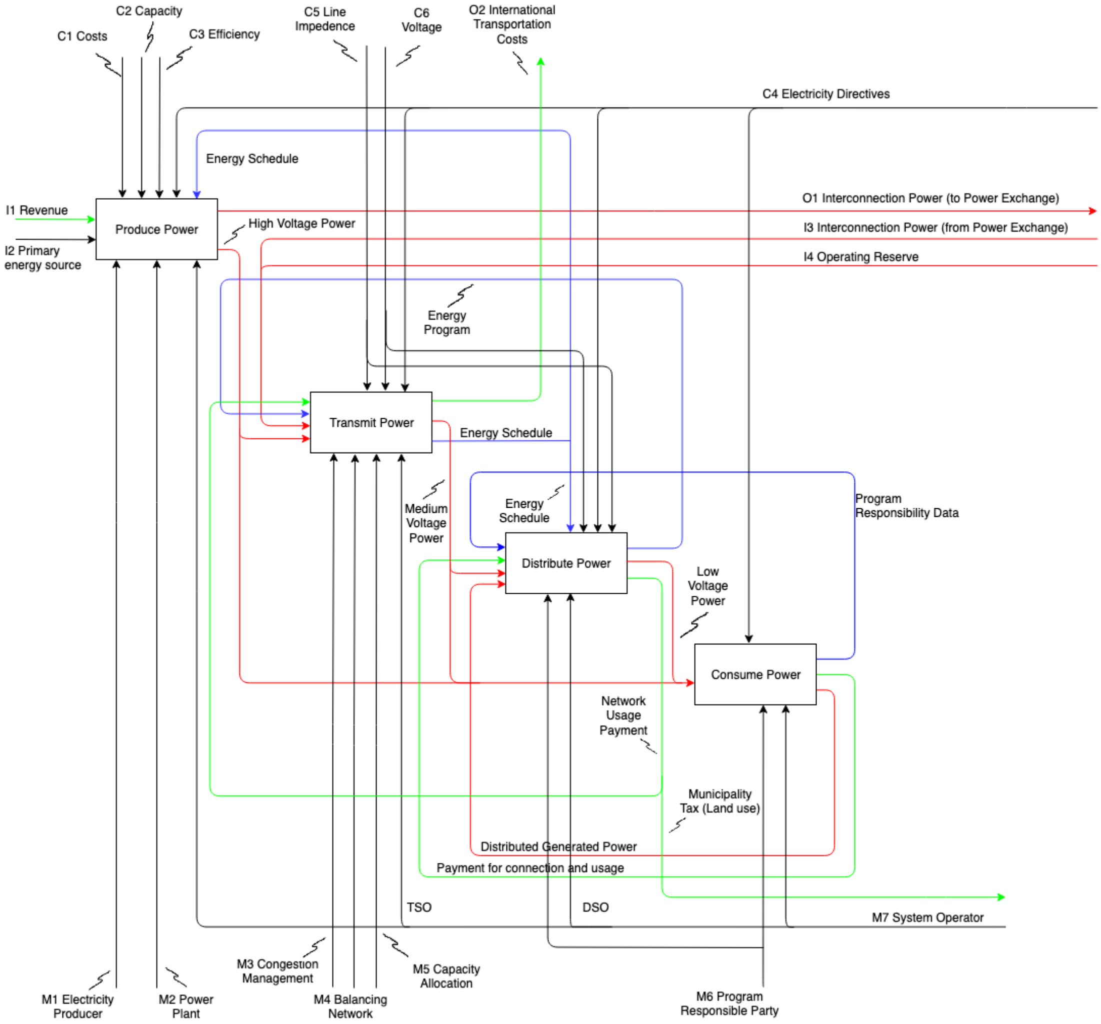
Store Gas. The *'Store Gas'* sub-system in the value chain represents the storage of gas before it is sent out for distribution. The inputs for this are the gas produced and gas transported, from the respective sub-systems, the mechanism for which is the Gas Transport Service. This sub-system is controlled as per the EU Gas Directives, and the output is gas exported to the wholesale market, and that sent forth for distribution.

Distribute Gas. The *'Distribute Gas'* sub-system is responsible for the distribution of gas that has been kept in storage and transported, which also forms the input to this sub-system. In addition to these, gas from the market, Consumption Revenue and Consumer Profile are also a part of the inputs. The mechanisms for this are Shippers and Distributed Network Operators, and this sub-system is controlled by the Dutch Gas Act, the EU Gas Directives, gas pressure and temperature. The outputs of this sub-system include the gas that has to be sent for consumption, program information and revenue from gas balancing (both of which form the input to the *'Transport Gas'* sub-system).

Consume Gas. The *'Consume Gas'* sub-system is the last sub-system of the value chain, and it receives as input, gas that must be distributed, with the mechanism as Distributed Network Operators. The controls of this sub-system are the Dutch Gas Act, gas pressure and temperature, whereas the outputs, i.e. Consumption Revenue and Consumer Profile (which are inputs to the *'Distribute Gas'* sub-system).

IDEF0 Model for Electricity Network Systems

The IDEF0 model of the electricity network system consists of four main sub-systems that interact with each other. These sub-systems are: Produce Power, Transmit Power, Distribute Power, and Consume Power.



IDEF0 model for electricity network system

Produce Power. The *'Produce Power'* sub-system is the first sub-system, that represents the production of power that is further to other sub-systems for final consumption. It has as its input from the primary energy source, and mechanisms such as the electricity producer, power plants (the physical entity that actually produces power), and system operator (who is responsible for ensuring that the system is always in balance, i.e. supply matches demand) that enable its functioning. This sub-system is controlled by the costs, capacity, efficiency, electricity directives, and the energy schedule which is obtained from the *'Transmit Power'* sub-system. Its output is the power sent via interconnectors to the Power Exchange, and High Voltage Power which is transmitted in the network (through the *'Transmit Power'* sub-system) and also fed to large customers directly (*'Consume Power'* sub-system).

Transmit Power. The *'Transmit Power'* sub-system is representative of power transmission for distribution. It has multiple inputs from various sub-systems, such as Network Usage Payment and Energy Program (both of which are obtained from the sub-system *'Distribute Power')* and High Voltage Power (from the *'Produce Power' sub-system).* Interconnection Power (from the Power Exchange) and power from the Operating Reserve are also inputs to this. Various mechanisms such as congestion management, network balancing mechanisms and capacity management are used here to ensure the transmission sub-systems works effectively. This sub-system is physically controlled by the line impedance, voltage and regulated by the Electricity Directives. It has as its outputs as the Energy Schedule which is sent to the *'Produce Power'* and the *'Distribute Power'* sub-systems, and Medium Voltage Power that is sent to the *'Distribute Power'* and *'Consumer Power'* sub-systems.

Distribute Power. The *'Distribute Power'* sub-system is the penultimate phase of the network system representing the distribution of power. It has as its inputs such as Program Responsibility Data, Distributed Generated Power (from distributed generators), payments for connection and usage (all of which are obtained from the *'Consume Power'* sub-system), and Medium Voltage Power (from the *'Transmit Power'* sub-system). The mechanisms for this sub-system include the System Operator and the Program Responsible Party (or Balance Responsible Party). It is controlled through the Energy Schedule (from the *'Transmit Power'* sub-system), Line Impedance and Voltage, and regulated by the Electricity Directives. The outputs of this sub-system are the Energy Program (which is an input to the *'Transmit Power'* sub-system), Low Voltage Power (which forms an input to the *'Consume Power'* sub-system), a Network Usage Payment (as revenue for the *'Transmit Power'* sub-system) and a Municipality Tax for land use.

Consume Power. The *'Consume Power'* sub-system represents the consumers who consume power. It has its inputs as High Voltage Power (from the *'Produce Power'* sub-system, Medium Voltage Power (from the *'Transmit Power'* sub-system) and Low Voltage Power (from the *'Distribute Power'* sub-system) depending on the type of consumer. The mechanisms employed here include a Balance Responsible Party (BRPs) and a System Operator, with Electricity Directives as the sub-system's control. The outputs of this are Program Responsibility Data, Distributed Generated Power and Payment for Connection and Usage (all of which are inputs to the *'Distribute Power'* sub-system). The end consumers pay for the energy, connection and capacity costs to the BRPs.

IDEF0 Model for Water and Wastewater Network Systems

The IDEF0 model of the water and wastewater network consists of four main sub-systems interaction with each other. These sub-systems are mainly: Produce Water, Distribute and Retail Water, Collect Wastewater, Consume Water and Produce Wastewater, and Treat Wastewater.

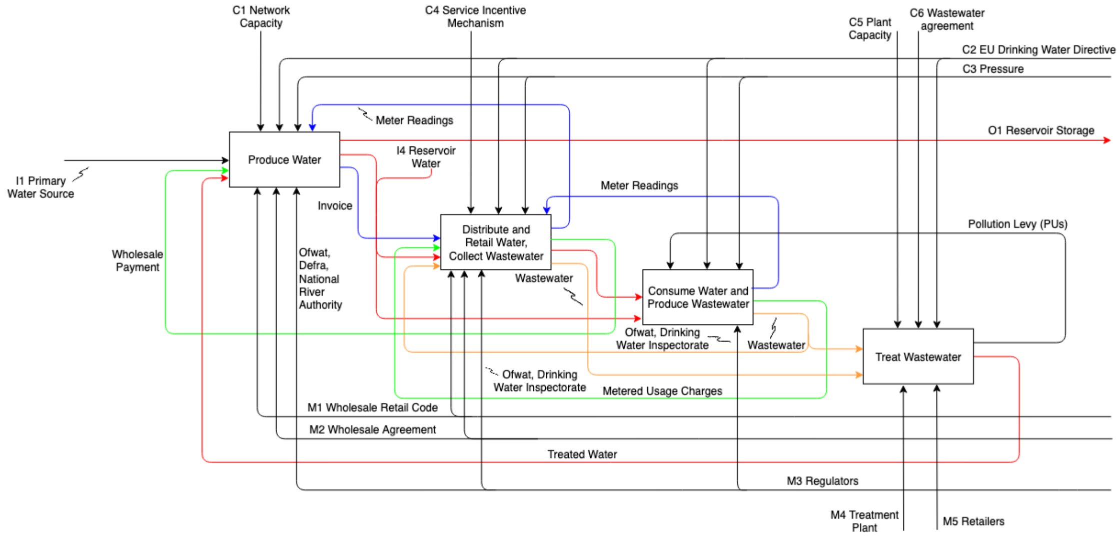


Figure 3: IDEF0 model for water and wastewater network system

Produce Water. The *'Produce Water'* sub-system in the model represents the production or abstraction of water from the primary water source. Other inputs such as wholesale payment (from the *'Distribute and Retail Water'*, *'Collect Wastewater'* sub-system), and Treated Water (from the *'Treat Wastewater'* sub-system) are also critical for abstraction and production of water. The mechanisms employed for this sub-system include the Wholesale Retail Code, Wholesale Agreement, the regulators. The controls include Network Capacity, the EU Drinking Water Directive, Water Pressure and Meter Readings (from the sub-system *'Distribute and Retail Water, Collect Wastewater'*). The outputs of this sub-system is water that is sent to reservoir for storage, and for further distribution downstream. In UK water markets, Ofwat, Defra, National River Authority are responsible for managing the water abstraction processes and ensuring quality for the consumers.

Distribute and Retail Water, Collect Wastewater. This sub-system, as the name suggests, is responsible for the distribution and retail of water, while simultaneously responsible for the collection of waste water. Inputs to the sub-system are Invoice (of water consumption generated from the *'Produce Water'* sub-system), and abstracted water or from the reservoir storage. The Wholesale Retail Code, Wholesale Agreement and the Regulators are employed as the mechanisms that facilitate the distribution and retail. To controls the sub-system, Service Incentive Mechanism (SIM), regulations such as the EU Drinking Water Directive and physical control parameters like Water Pressure, Meter Readings are set up. The sub-system provides water to the consumers, and generated wastewater to the *'Treat Wastewater'* sub-system.

At present there are around 12 water and sewerage companies and 9 water only companies operating across the UK. The regulation of the operation of these companies is done by Ofwat, Drinking Water Inspectorate and Environmental Agency. The wholesaler owns the network and provides water and sewerage service to the customers in the region. The retailers are responsible for providing value added services such as meter readings, grievance redressal etc. The wholesaler is paid for by the retailer who in turn sends the bills to the consumer.

Consume Water and Produce Wastewater. This sub-system represents the consumption of water along with the production of wastewater in the value chain by consumers. The controls include Pollution Levy (PUs) (output from the *'Treat Wastewater'* sub-system), the EU Drinking Water Directive and physical control of the pressure in the pipeline. The output of this sub-system include consumption meter readings, Metered Usage Charges, and wastewater. These are sent back as input to the *'Distribute and Retail Water, Collect Wastewater'* sub-system, and to the *'Treat Wastewater'* sub-system).

Treat Wastewater. The 'Treat Wastewater' sub-system is responsible for the treatment of wastewater, and thus, its input is wastewater obtained from the *'Distribute and Retail Water, Collect Wastewater'*, and the *'Consume Water and Produce Wastewater'* sub-system. Its mechanisms include treatment plant and water retailers. The control input includes plant capacity, wastewater agreement between consumers and retailers, and the EU Drinking Water Directive. This sub-system's outputs are Pollution Levy (PUs) which are the control parameters for water quality for the *'Consume Water and Produce Wastewater'* sub-system, and treated water which is sent as input to the *'Produce Water'* sub-system.