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Hydrogen as energy carrier - the missing piece in the heat transition puzzle?

Developing a decision-making model for a prioritization of neighbourhoods suitable for the application of hydrogen for heating purposes

Master thesis Society, Sustainability and Planning

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Abstract

In 2021, the built environment as an energy end-use sector accounted for around 14% of all energy consumption in the Netherlands with more than 90% of its heating provision based on the combustion of natural gas. While the increasing use of renewable energy sources and sustainable energy carriers calls for a transition in the socio-technical system characterized by an interrelation between socio-institutional and technical-spatial components, hydrogen as energy carrier is seen as a promising sustainable alternative in the heat transition of the Dutch built environment. Furthermore, while the existing gas distribution infrastructure on the local level has the potential of being repurposed for hydrogen transport, the spatial allocation of hydrogen as energy carrier for heating purposes is subject to uncertainty. Faced with a complex decision-making process involving many stakeholders and various considerations, the allocation of hydrogen becomes a spatial planning matter in which competing claims on scarce resources and limited spaced must be balanced.
It is therefore important to identify relevant criteria on the local level that influence the decision where the application of hydrogen for heating purposes is *most* suitable. An understanding of both the potential position of hydrogen as energy carrier in the heat transition of the Dutch built environment and the technical fitness of the existing gas distribution infrastructure for transporting hydrogen is beneficial to develop the decision-making model. For this purpose, this study makes use of the *analytical hierarchy process* (AHP) approach employing a combination of interviews, a questionnaire and focus group.

In total seven relevant criteria on the local influencing the decision regarding the allocation of hydrogen as energy carrier in the built environment have been identified. While all the criteria have an either explicit or implicit spatial component, the comprehensive spatial demarcation is not possible for all of them because of ambiguous definition or complex spatial composition. What is more important, the results showed that hydrogen as energy carrier will have an important role in the heat transition due its ability to compensate for the shortcomings of electricity and its grid, and that the existing gas distribution infrastructure is technically suitable for hydrogen transport.

This research confirms the complexity stakeholders are faced with regarding sustainable energy planning in the built environment and the interrelatedness of the various components of socio-technical energy system. However, the development process shows that such a decision-making model can function as a good communication tool between stakeholders in order to stimulate knowledge exchange and reaching consensus on pertinent issues. It is recommended that identified shortcomings of the current approach for developing a heat transition map for the built environment should be resolved.

Keywords: Decision-making in spatial context, socio-technical energy systems, heat transition, hydrogen as energy carrier, local scale

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List of abbreviations

ACM	Authoriteit Consument en Markt (Consumer and Market Authority)
CBS	Centraal Bureau voor de Statistiek (Statistics Netherlands)
CDW	Construction and demolition waste
CH_4	Methane (main constituent of natural gas)
CO_2	Carbon dioxide (main greenhouse gas)
CLO	Compendium voor de Leefomgeving (Environmental Data Compendium)
DNV	Det Norske Veritas (International accredited registrar)
ECW	Expertise Centrum Warmte (Heating Expertise Centre)
EU	European Union
H_2	Hydrogen gas (dihydrogen)
HTV	Hoge temperatuur verwarming (high temperature heating)
IRENA	International Renewable Energy Agency
NBR/SBR	Synthetic rubber types
NWP	Nationaal Waterstof Programma (National Hydrogen Program)
PBL	Planbureau voor de Leefomgeving (Environmental Assessment Agency of the Netherlands)
PJ	Peta Joule (unit of energy in general scientific applications)
RVO	Rijksdienst voor Ondernemend Nederland (Netherlands Enterprise Agency)
SodM	Staatstoezicht op de Mijnen
TSO	Transmission System Operator (Dutch: netbeheerder)
Vesta MAIS	Vesta Multi Actor Impact Simulatie (spatial energy model)
WFD	Waste Framework Directive

Glossary

Built environment	In this study, the built environment is referred to as the entirety of buildings (houses, offices, public buildings) that are considered in the heat transition vision of the municipality and that consume energy for heating purposes (PBL, 2020).
Decarbonization	The process of decarbonization refers to reducing carbon dioxide (CO_2) emissions resulting from human activity towards zero (Klimaatakkoord, 2019.
Energy end-use sector	In this research the built environment is the energy end-use sector under study. It is a category of energy consuming entities characterised by a certain energy demand and energy use. Energy-end use sectors in the downstream use two types of energy: thermal and electrical (Rosen, 2004). In this study, only the thermal energy use is considered.
Energy carrier	An energy carrier is a substance (fuel or gas) or phenomenon that contains energy that can be converted later to other forms such as mechanical work or heat (TU Delft OCW, n.d.). In this study the hydrogen as energy carrier and heat are of particular interest.
Energy production, generation and storage	According to the first law of thermodynamic, energy cannot be produced, lost or wasted. Only conversion from energy source to an energy carrier is possible (Guggenheim, 1985).
Energy source	An energy source is any substance, force of the result of this can be used to produce energy carriers (while acknowledging the laws of thermodynamics) (Guggenheim, 1985). In this study the use of renewable sources, such as wind and solar energy, converted to green hydrogen as energy carrier is of particular interest.
Energy supply system	In this study an energy supply system encompasses the extraction, transmission, generation, distribution and storage of energy

	carriers (Solmes, 2009). Next to that, the consumer (built environment as end-use sector) and institutions make part of the system.
Energy infrastructure system	In this study the energy infrastructure system considers all physical/material components needed for the distribution and storage of a gaseous energy carrier. Therefore, components such as pipes and stations are part of this.
Energy transition	The energy transition encompasses a multiple-dimensional shift from unsustainable fossil fuels (energy sources and carriers) towards sustainable non-fossil fuel energy sources (such as wind and sun) and energy carriers (such as hydrogen). The multiple dimensions refer to changes in consumption behaviour, spatial demand and supply patterns, and visibility of energy generation (WEC, 2014).
Heat transition	The heat transition is an essential part of the energy transition, focussed on the heating supply system of the built environment. It encompasses the transition from heating on fossil fuel towards sustainable heating applications, such all-electric, district heating networks or sustainable gasses (such as hydrogen) (PWC, n.d.).
Heat transition vision/map	A heat transition vision/map is a policy document drawn up each municipality (since 2021) that gives a first direction to the approach to insulating the existing housing stock and making the built-environment gas-free. In here, each neighbourhood gets a sustainable heating alternative assigned to it.
Hydrogen application	In this study, the term ‘hydrogen application’ refers to the use of hydrogen as energy carrier for heating purposes in the built environment through the use of a gas-fired boiler.
Local scale	In this study, the local scale is spatially defined by the juridical borders of the municipality.

Neighbourhood scale	In this study, the neighourhood scale refers to the 'smallest' spatial scale identified in the Netherlands where data is collected on by the national government. The so-called 'CBS-buurt' is demarcated based on historical or spatial homogenous characteristics.
Network operator (regional)	A network operator, also called a distribution system operator, is responsible for the energy distribution system which delivers gas and electricity to most end users (Vattenfall, 2022). In this study, the regional network providers are of particular interest due to their responsibility of transporting gaseous energy carriers for heating purposes to the built environment as end-use sector.
Sustainable energy supply	In this study, a sustainable energy supply is characterized as adhering to aspects of 'general sustainability' defined by the WCED (1987) with a keen focus of meeting the needs of present and future generations in terms of energy provision. Therefore, it is an energy supply that uses only renewable energy sources.
Sustainable heating alternative	In line with a sustainable energy supply, sustainable heating alternatives [*for the built environment*] are heating applications that not run on fossil-fuels, but make use of renewable energy sources (wind/sun) or sustainable energy sources (hydrogen or hot water) Kugler et al., 2022).
Technical fitness	Technical fitness denotes how effectively a capability or physical structure performs an intended function [*when normalized by cost*] (Heltfat, 2018). In this study, the technical fitness of transporting hydrogen (as intended function) through existing local gas distribution infrastructure (as physical structure) is considered.

1. Introduction

While the built environment accounts for approximately 30% of global energy consumption, it generates around 20% of all energy-related greenhouse gas emissions (Beccali, 2017). In accordance with the Paris Agreement limiting global warming to 1.5°C (United Nations, 2015), the Netherlands committed itself to reaching zero-net emissions by 2050 (Klimaatakkoord, 2019). As the current heat provision of the Dutch built environment is 90% based on the combustion of natural gas (Bekker, 2019), this poses a great challenge for realising the Dutch climate policy regarding the provision of an alternative to natural gas in the heat provision of the built environment by 2050 (Klimaatakkoord, 2019).
The transition towards a sustainable energy supply for the urban landscape necessitates not only the increased use of renewable energy sources and sustainable energy carriers such as hydrogen (Younis et al., 2022) also serious reconfigurations in the current socio-technical energy system (Elzen et al., 2004). While the introduction of hydrogen as energy carrier for heating purposes could contribute to the repurposing of existing gas distribution infrastructure (Alliander, n.d.; Stedin, n.d.), the application of hydrogen in the built environment is characterized by many uncertainties (Giegler & Weeda, 2018; Weeda & Niessink; 2020). Within the heat transition vision of every municipality in the Netherlands a sustainable alternative to fossil-fuel based heating applications for each neighbourhood is proposed (RVO, 2019). While assigning a district-heating network or an all-electric solution to a neighbourhood - both being acknowledged as the most prominent alternatives (PBL, 2020; Weeda & Niessink; 2020) - is rather straightforward based on, among others the spatial built-up, building typology or construction year (PBL, 2020; PBL, 2022), the spatial allocation of hydrogen as energy carrier is subject to ambiguity.
Faced with a complex decision-making process due to both ambiguity and uncertainty regarding hydrogen as energy carrier in the built environment and the involvement of many stakeholders in such a decision (RVO, 2019), this make it a spatial planning matter in which multiple criteria have to be identified and weighted in order to manage competing claims on scarce resources and limited space (Gusatu et al., 2022), especially in a rather small but dense populated country like the Netherlands (Tisma & Meijer, 2018).

Hence, this research explores the potential position of hydrogen as energy carrier in the built environment and develops a decision-making model for identifying a prioritization of neighbourhoods suitable for the application of hydrogen for heating purposes.

1.1 Research objectives

The main objective of this research is to develop a decision-making model in a spatial context, based on multi criteria analysis approach, that supports various stakeholders active on the local municipal level such as policy makers, spatial planners, or network operators in making an informed decision about where to apply the energy carrier hydrogen as sustainable alternative for heating purposes in the built environment. Several issues need to be addressed in order to deliver the necessary input for achieving this main objective:

First, the potential position of hydrogen as energy carrier for heating purposes in a sustainable energy supply system in the built environment is investigated. While the energy transition and more specifically the heat transition [*due to the context of this study*] is expected to result in a fundamentally different energy supply, therefore different infrastructure system (Elzen et al., 2004) due to an increasing input of renewable energy carriers (De Boer & Zuidema, 2013), irreversible changes in the existing socio-technical energy infrastructure system are necessary (Geels, 2011). In order to assess how much the technical components of the current energy infrastructure system change, the potential position of hydrogen as energy carrier in the heat transition needs to be identified, as this is currently lacking for the built environment (Gigler & Weeda 2018).

Secondly, despite the current energy infrastructure system will require extensive adaptations due to the increasing insertion of renewable energy carriers (De Boer & Zuidema, 2013; Elzen et al., 2004) the possibility of repurposing certain components of the energy supply system for hydrogen transportation offers the possibility to both postpone decommissioning of existing infrastructure components (Aarnes & Monsma, 2021; Banet, 2022) and to reduce construction and demolition waste (Hendricks and Dordthorst, 2001). Hence, this research aims to identify the technical fitness of certain components of the gas transport infrastructure system for being repurposed in order to transport hydrogen through the local gas grid delivering sufficient energy [*in caloric equivalents*] to meet current heating demand in the built environment. As being elaborated on in more detail in **section 1.4**, this study focuses on the components that are subject to the area of responsibility of regional network providers.

Third, in order to steer the spatial allocation of hydrogen as energy carrier for heating purposes in relation to the issues outlined above, a decision in such a complex spatial context is required (Greene et al., 2011). Since decision making in a spatial context involves a large variety of possible alternatives (Malczewski, 2006) such as the number of neighbourhoods within a municipality, a suitable analysis approach needs to be chosen, followed by the identification of relevant criteria that will be included in the analysis (Saaty, 2008). Inherent to the chosen analysis approach comes a decision rule determining how the criteria factor in the decision, which needs to be computed. While dealing with a spatial decision problem in the context of this study, the identified criteria need to be spatially demarcated in a way useable for a spatial analysis (Greene et al., 2011).

Finally, when the three above-described objectives have been comprehensively addressed, the findings are combined to develop a decision-making model that can be used as a 'quick scan'-method for approaching the decision in which neighbourhood the application of hydrogen as energy carrier is most suitable.
A tool, like this decision-making model, that improves communication between various stakeholders has positive influence on the planning process (Billger et al., 2016), especially in both the complex context of energy landscaping and given the Dutch consensus-based planning culture (Woltjer, 2017).

1.2 Research questions

Succinctly, this research focuses on the identification, weighing and spatial demarcation of relevant criteria influencing the spatial decision-making model in relation to the potential position of hydrogen as energy carrier in the built environment and technical feasibility of hydrogen transport through the existing gas transport infrastructure.

Therefore, the main research question of this study is formulated as:

"How can a multi-criteria analysis in a spatial context inform the prioritization in neighbourhood selection suitable for the application of hydrogen as energy carrier for heating purposes in the built environment in the Netherlands?"

In order to be able to answer the main research question satisfactory and to produce relevant outcome for the research objectives outlined in the previous section, these objectives have been translated into the following sub-questions:

1. What is the potential position of hydrogen as energy carrier in the heat transition of the built environment?
2. To what extent is the existing gas transport infrastructure on the local scale from a technical perspective suitable for providing the required amount of energy in the built environment when using hydrogen as energy carrier for heating purposes?
3. Which relevant criteria can be identified on the local level that inform a spatial multi-criteria analysis for prioritizing suitable neighbourhoods for the application of hydrogen as energy carrier?
4. What are relative weights of the relevant criteria explaining their importance in the overall decision-making?
5. How can the identified criteria for the multi-criteria analysis be defined and spatially demarcated?

1.3 Relevance of this study

1.3.1 Societal

The social relevance of this study can be framed according to how the outcome of this research contributes to both answering questions that society asks and to solve problems it faces (RUG, 2021). First, in line with goals of the Paris Agreement on international level (United Nations, 2015) and the Dutch climate agreement (Klimaatakkoord, 2019) to decarbonize society until [*the latest*] 2050, this research adds to the body of knowledge regarding the potential position of hydrogen in the heat transition of the built environment [*in the Netherlands*]. Currently, it is unclear how the various sustainable alternatives of [*predominantly*] natural gas are positioned into the framework of the heat transition, and what the allocation of scarce hydrogen is and more specifically under what spatial-technical conditions the application of hydrogen as energy carrier in the built environment is [*most to least*] suitable.
Secondly, while facing the biggest reconstruction/renovation with regard to the energy infrastructure system and built environment of the Netherlands ever (Klimaatakkoord, 2021; Rotmans, 2021), this study aims to contribute to the body of knowledge about the possibilities to repurpose the existing gas infrastructure for hydrogen transport on the local level. As such, the findings of this research and the corresponding implications for planning practice

contribute to the reduction of the spatial impact of the reconstruction of [*predominately the local level in*] the Netherlands through making [*smart*] use of existing infrastructure.

Additionally, due to hydrogen's potential of catering for high-temperature heating (Dutch: hoge temperatuur verwarming, HTV), in contrast to other sustainable heating alternatives such as district heating or pure all-electric solutions (ECW, 2020), the application of hydrogen as energy carrier in the built environment provides an emission-free heating in both buildings that are difficult to insulate and spatial areas, where the construction of a district heating network is not possible from a spatial perspective (due to lack of space in the underground) or the electricity net reinforcement is not economic (Rijkswaterstaat, 2017).

1.3.2 Theoretical

In terms of theoretical relevance, studying the phenomenon of hydrogen applications in the built environment is important in three ways, following the research objectives. First, this research aims at identifying the potential position of hydrogen as energy carrier in the heat transition, as well as briefly in the wider context of the dynamic energy transition. While an increasing amount of policy ambitions are formulated and national strategies regarding hydrogen are drawn up (Klimaatakkoord, 2019; NWP, 2022; PBL, 2020), knowledge on the potential position in the [*local*] heat transition from the perspective of other stakeholders is currently lacking. Research on this topic is suggested to be beneficiary for a better-managed transition in terms of hydrogen applications (Gigler & Weeda, 2018; McDowall, 2014). Additionally, identifying the potential position of hydrogen in the heat transition can contribute theoretically to the discussion on repurposing existing gas infrastructure in terms of prolonging its lifespan (Banet, 2022), therefore decreasing the need for premature decommissioning (Kemfert et al., 2022).
Secondly, considering the application of hydrogen [*as energy carrier*] in the built environment as a niche innovation in the current socio-technical energy system (Smit et al., 2007), this study examines the spatial-technical feasibility of its transport through existing local infrastructure in the Dutch context.
Finally, while decision-making models including hydrogen as energy carrier are considered only in relation to other sustainable heating alternatives in the built environment (PBL, 2020; PBL, 2022, Weeda & Niessink; 2020) or examined from an economic perspective (Hoogervorst, 2020; Hoogett; 2020), this study focuses exclusively on hydrogen. As such, this research contributes to the body of knowledge of in which area's [*considering the neighbourhood scale*] the application of hydrogen for heating purposes is suitable from a technical-spatial perspective.

1.4 Research scope

In light of recurring and prolonging discussions on how to provide the built environment with an energy system that supplies sustainable heat on the Dutch national government level (PBL, 2022; Rijksoverheid, 2022) and corresponding actions of municipalities to draft implementations plans (RVO, 2019; or see for examples: Gemeente Groningen, n,d,; Gemeente Rotterdam, 2021) , the attention for hydrogen as potential energy carrier in the built environment is increasing consistently (CE Delft, 2017; Topsector Energie, 2018; Weeda & Niessink, 2020). An increasing number of pilots on various scales involving different building typologies and construction periods are currently explored or are already taking place

(Alliander, 2022; Enexis, 2022; Gemeente ***********, 2023, Stedin, 2022). While at all government levels the awareness of the need for a systematic change in energy system [*for the built environment*] is accruing stepwise (Klimaatakkoord, 2019; Rijksoverheid, 2016), the national gas infrastructure and transport company (GasUnie) as well as several regional network providers are looking into and experimenting with the potential use of existing gas infrastructure for hydrogen transport for some while (GasUnie and Tennet, 2019; Liander, n.d.; Stedin; 2018).
Furthermore, discussing transitions in energy supply systems involves social and technical components. While both components are highly interrelated through their historically evolution characterized by path-dependence as shown for example in the development of the Dutch gas system (Loorbach et al., 2008), this study focuses on the technical specifications of the current energy infrastructure system for local gas transport and therefore adopts a rather spatial-technical lens when researching the intended prioritization of neighbourhoods of hydrogen application, and only briefly touches upon social aspects. In line with this, only the technical fitness of the existing local gas grid (from the regional entry point up to the gas meter) is studied regarding its repurposing potential.
Finally, while the decision where hydrogen as energy carrier in the built environment is applied is influenced by factors on multiple spatial and therefore governmental levels (Hoogervorst, 2020; NWP, 2022), this study focuses on the local level only.

1.5 Research approach

The study at hand is divided into two successive phases illustrated in figure 1. While the first phase is focused on literature-based research providing background information about hydrogen as energy carrier and laying the theoretical foundation of transition theory in relation to socio-technical energy systems, the second phase uses the information obtained in the first phase as starting point for an empirical explorative study with as goal to develop a decision-making model in a spatial context.

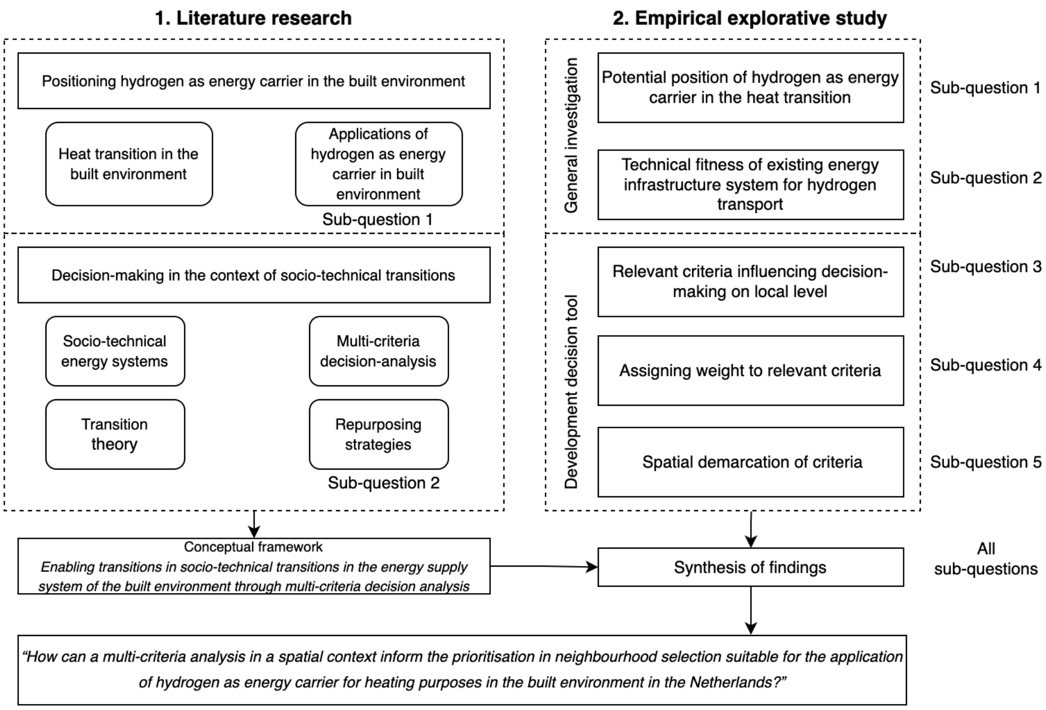

Figure 1: Research approach applied in this study

The first research phase positions the topic of interest [*hydrogen as energy carrier*] in the wider context of the energy transition (**chapter 2**) and elaborates on how transitions in technical environments take place (**chapter 3**).
First, a socio-technical system framework will be established to better understand the process of transitions in energy systems, and consequently how hydrogen as energy carrier can be fitted into the current heating system of the built environment which is based predominantly on the combustion of natural gas (sub-question 1). Secondly, using the waste management hierarchy as a starting point, the technical feasibility of using existing gas infrastructure to transport hydrogen is investigated in relation to repurposing strategies (sub-question 2). Thirdly, a suitable multi-criteria analysis approach is identified which gives steering to the development of the decision-making model. Finally, the steps executed in this first phase result in a framework conceptualising the potential pathway when transitioning towards hydrogen as energy carrier in the built environment (**section 3.5**, figure 7)

The second stage of this research follows the steps sketched by the identified multi-criteria analysis approach. The aim of this explorative study is to develop a decision-making model that could be used to identify a prioritization of suitable neighbourhoods for the application of hydrogen as energy carrier. Using different data collection techniques (**chapter 4)** a quick-scan version of such a model is developed. While relevant criteria influencing such a decision-making model are identified through semi-structured interviews (sub-question 3), these are individually weighted using a questionnaire (sub-question 4). During a final focus group, the criteria are spatially demarcated, followed by again individually weighing (sub-question 4). Together with the outcomes of the literature review, and the input on more general questions on the technical feasibility and successive application of hydrogen in the built environment, these form the basis for implications for the planning practice, presented in **chapter 7**.

1.6 Structure of this study

On the prior pages an introduction to the background of this research's topic, an overview of the research objectives with corresponding research questions and the relevance of this study was given. In **chapter 2** an introduction into the topic of hydrogen as energy carrier, it's position in the wider context of the energy transition and its potential application in the built environment. **Chapter 3** provides the reader with a comprehensive literature review on socio-technical energy systems, transition theory, repurposing strategies for energy infrastructure and [*geo-based*] multi-criteria analysis regarding energy landscape planning, as well as a conceptual model which guides the rest of this study. The methodology of this study can be found in **chapter 4**, elaborating on the research strategy including data collection methods and analysis techniques. While in **chapter 5** the results of the study are presented, a critical discussion of these results in relation to the literature followed by a conclusion on the main research question is drawn up in **chapter 6**. The last chapter elaborates on whether the research objectives are met, critically discusses the suitability of the methods used and provides recommendations for further research on the application of hydrogen as energy carrier in the built environment and on decision-making in relation to hydrogen applications in the heat transition [*as a realistic assumption is that not all aspects relevant can be covered in a single research by one researcher given the time limited of this research*].

2. Positioning hydrogen as energy carrier in the built environment

The aim of this chapter is to position hydrogen as energy carrier in the built environment in the wider context of the energy transition in the Netherlands. First, the energy characteristics of the built environment including different potential applications of hydrogen in the built environment are outlined. Secondly, a short introduction of the principles for hydrogen production, distribution and storage is provided. Lastly, the [Dutch] heat transition of the built environment is briefly introduced.

2.1 Energy supply and demand in built environment

The potential position of hydrogen as energy carrier is among others dependent on the characteristics of the supply and demand patterns in the built environment. The built environment is considered as a so-called end-use sector (Eurostat, 2018), where energy is directly used by the user. Given the scope of this research on hydrogen as energy carrier in a gaseous form, potential applications in the built environment are space and tap water heating and cooking (Eurostat, 2023; Dodds et al., 2015). However, the flame of hydrogen is invisible making it rather unattractive for conventional cooking installations (KIWA, 2018).
In 2021 the built environment accounted for around 14% of all energy consumption [*taking all energy carriers and sources into account*] in the Netherlands (see figure 1, where '*househoudens'* are considered as households in the built environment), which translate to approximately to 300PJ. Around 80% of all energy used in the built environment relates to natural gas combustion for space and tape water heating (CLO, 2023).

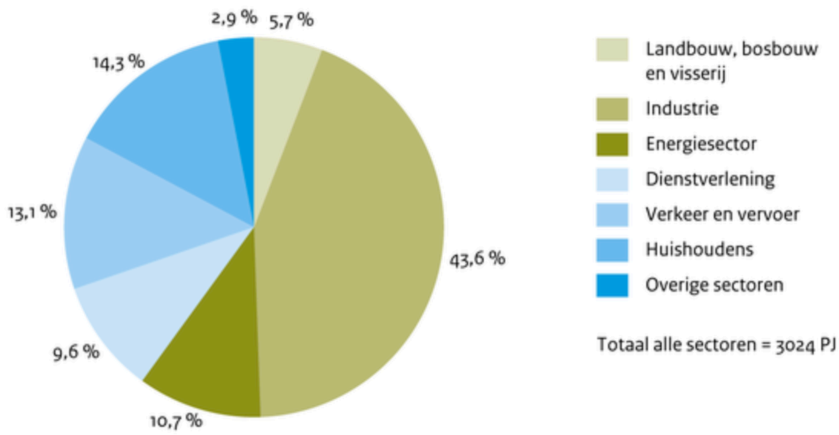

Figure 2: Overview of energy consumption by end-users in the Netherlands, 2021 (Source: CLO, 2023)

2.1.1 Hydrogen application in the built environment

While hydrogen can be used directly [*via combustion*] or indirectly [*via a stationary fuel cell*] or heat supply (Edwards et al., 2007), this research focuses only on the direct heat supply. The direct heat supply through hydrogen works in the same way as with natural gas combustion in a gas-fired boiler. Hydrogen entering the individual building via the local gas distribution system is transferred via indoor pipes to the boiler suitable for hydrogen (Detz et al., 2020). Existing gas appliances cannot [*easily*] be made suitable for hydrogen because the combustion rate of hydrogen is considerably higher than that of methane which might result in flame strike and damage to the boiler (KIWA, 2018). Therefore, replacement of the gas boiler is

necessary (Stedin, 2022). The generated heat by the combustion of hydrogen is then used to heat water circulating in a conventional central heating system (Dodds et al., 2015).
While direct heat supply by the combustion of hydrogen as energy carrier in a suitable boiler might also be applied on the neighbourhood scale as component of a district heating network (Detz et al., 2020), this research focuses on the application on the individual building scale.

2.2 Intermittency problem and system integration

The energy consumption demands of the built environment are subject to daily and seasonal variations (Van Kann, 2015) due to specific patterns in usage of buildings and behaviour of users (Ward, 2008; Woo & Cho, 2018). Most buildings like schools, offices and public buildings are only heated when it's cold outside (in the winter) and when they are used (over day). While the current energy supply system [*mainly*] based on the combustion of fossil fuels, like gas, oil and coal, is able to cope with the variations in energy demand simply through the adjustment of input rates (Ramesh, 2017), most sustainable energy sources like wind and sun are subject to both daily and seasonal variations (Heide et al., 2010). Taking the goals of the Dutch government to increase the share of renewable energy sources (Rijksoverheid, n.d.) as baseline, the daily and seasonal variation in both energy demand and supply patterns might cause an intermittency problem (Younis et al., 2022).

While solar and wind power are projected to make an increasing contribution to a low-carbon energy supply in the future, the limited predictability of these energy sources pose a challenge to their large-scale integration into the current energy supply system (Younis et al., 2022). Next to that, sustainable energy sources are subject to geographical constraints, leading to a potential mismatch between the location of supply [*like the location of a windfarm on the North Sea*] and demand [*like the location of a neighbourhood elsewhere in the Netherlands*] adding to the complexity of energy planning (Vettorato et al., 2011). Still, system integration based on the principle of 'mixing' different energy sources is considered as an opportunity to cope with the intermittency problem and can therefore play an important role in the energy supply of the built environment (Clastres, 2011; Younis et al., 2022).

2.3 Production, transportation, storage of hydrogen

2.3.1 Production

While hydrogen is the most abundant element on earth, under normal circumstances hydrogen atoms are bound to other elements, especially oxygen in the form of water (H_2O) and carbon in the form of methane (CH_4) the main component of natural gas. Therefore, hydrogen is almost non-existent in nature and must be produced (Weeda & Niessink, 2020). In general, two methods for hydrogen production can be distinguished (Gondal, 2019; Holladay et al., 2009), considering the used source: carbohydrate-based and water-based methods (electrolysis). Given the underlying research agenda of this research focussing on sustainable energy supply for the built environment, only the latter method is considered.
Various processes can be used to produce hydrogen using [*water*] electrolysis, which achieve different levels of energy efficiency due to specific technologies, materials, current densities, and temperatures. The three main types of electrolysers are: Alkaline, Proton Exchange Membrane (PEM) and Solid Oxide (Frauenhofer IKTS, n.d.; Gondal, 2019). While the various

operating parameters of these electrolysers are not further discussed in this research, the main principle is using electricity to split water into hydrogen and oxygen obtaining two hydrogen molecules (H_2) and one oxygen molecule (O_2) from two water molecules (H_2O).
The most significant limitation of large-scale application of hydrogen as energy carrier identified is, based on its above-described characteristics, the fact that it needs to be generated using other energy carriers [*namely sustainable electricity*]. While the process of electrolysis generates heat as a 'by product', a loss of energy efficiency is inherent to the production of hydrogen using electrolysers (Armaroli & Balzani, 2011; Gondal, 2019).

2.3.2 Transportation and storage

While hydrogen can be transported in various ways like among others in a liquid form such as ammonia (IRENA, 2019), considering the aim of this research (see **section 1.2**) only the transport of gaseous hydrogen in pipelines will be elaborated on. Just as natural gas, hydrogen can be transported through pipelines (Gigler & Weeda, 2018). Depending on the timing and both the location of production and consumption of hydrogen the current high-pressure infrastructure grid for natural gas could be used for this in the Netherlands (Aarnes & Monsma, 2021). While some aspects concerning the technical suitability of transmission pipelines have to be acknowledged (Gondal, 2019), investments for readjustments are considered as minor compared to construction of new infrastructure. The transport of hydrogen as energy carrier through the local gas distribution system is discussed in greater detail in **section 3.3.1**.

The storage of hydrogen in a gaseous form can be done in four ways. Storage in [*repurposed*] gas pipelines as line pack, salt caverns, aquifers and fittings. While the (potential) storage in aquifers is limited due to the presence of sulfidogenic bacteria responsible for the generation of hydrogen sulphides, no technical limitations have been identified for the other storage possibility so far (Gondal, 2019). Depending on how much volume needs to be transported, how long it needs to be stored and the geographical availability of different options, hydrogen can also be stored in storage tanks (Hoggett, 2020).

2.4 The heat transition of the built environment

While the heat provision of the built environment is currently based for more than 90% of the combustion of natural gas [*when considering individual buildings and heating networks*] (Bekkers, 2019), the Dutch government decided to phase out natural gas consumption in the built environment by 2050 (Klimaatakkoord, 2019). In general, the heat transition is concerned with the decarbonisation of the heating supply in the built environment through the provision of a sustainable heating alternative (RVO, 2022).

2.4.1 Dutch heat transition

According to Dutch climate agreement (Klimaatakkoord, 2019), municipalities are the directors of the heat transition in the built environment. Together with property owners, residents, regional network providers and fellow government authorities [*especially in line with Regional Energy Strategies of the Provinces*], they drafted a heat transition vision (Dutch: transitievisie warmte) by the end of 2021. It contains a sustainable alternative for natural gas for each neighbourhood in their area. The most common alternatives are an [*individual*] all-electric solution, a district heating network or a hybrid solution where a heating pump is combined with a sustainable gas either green gas or hydrogen (RVO, 2022).

While each municipality has to draft their own individual heat transition vision, the national government provides a so-called ‘start analysis natural gas free neighbourhoods’ (PBL, 2020; 2022) consisting of a technical-economic analysis based on the Vesta MAIS model which provides the national cost of the various sustainable heating alternatives at neighbourhood level for the whole Netherlands.

Hydrogen in built environment according to the Dutch government

In relation to the application of hydrogen as energy carrier in the built environment the PBL discusses two main factors, namely the demand and availability. While projections about the demand of hydrogen in the built environment are vastly spread considering the spatial allocation or the total demand in petajoule (PJ), hydrogen is considered to play a role in buildings that are either difficult to insulate or in areas not suitable for other sustainable alternatives (Hoogervorst, 2020). While this goes in line with what the NWP (2022) projects about the spatial allocation of hydrogen, they (NWP, 2022) urge municipalities for not taking hydrogen as possible alternatives in these areas for granted. Additionally, an important notion highlighted by different authors (NWP, 2022; PBL, 2020, 2022; Weeda & Niessink, 2020) is that the assessment of where to apply hydrogen as energy carrier should always be done in an integral way, considering the other sustainable alternatives.

Regarding the availability of hydrogen general, consensus (Gigler & Weeda, 2018; NWP, 2022; PBL, 2020; Weeda & Niessink, 2020) exists that neither large volumes nor large-scale availability (location-wise) will be realistic for the built environment before 2030. For the period after 2030 different potential scenarios are acknowledged and thus uncertainties regarding decision-making are fundamental and challenging. Depending on the experiences from the hydrogen pilot projects [*in the built environment*] (NWP, 2022), the availability of infrastructure to transport hydrogen not only between the big industry clusters but also towards residential areas (CE Delft, 2017; Gigler & Weeda, 2018) and the national production capacity (Hoogervorst, 2020) the share of housing stock heated by hydrogen can be up to 30% (Hoogervorst, 2020).

3. Theoretical framework

3.1 Socio-technical systems

> "*A number of innovations in work organization […] have been making a sporadic and rather guarded appearance since the change-over of industry to nationalization. (…). They have been accompanied by impressive changes in the social quality of the work-life of face teams*." (Trist & Bamforth 1951, p. 3 – 4)

> "*A great network of power lines which will forever order the way in which we live is now superimposed on the industrial world. […] have ordered the man-made world with this energy network*." (Hughes 1983, p. 1)

While being published with an over 30 years' time lag, both above-quoted articles by Trist & Bamforth (1951) and Hughes (1983) can be identified as the theoretical origin of the concept 'socio-technical systems' (Sovacool et al., 2018). Highlighting the integration of physical assets (such as infrastructure) with the human environment (such as user practices) both articles have examined the concept from the two discrete yet interconnected perspectives (Cooper & Foster, 1971). While the work of Trist & Bamforth (1951) focused on social reorganization of the work routine [*of coal mine workers*] through the introduction of technological innovations, Hughes (1983) based his work on the development of large technical systems in the power sector within a changing institutional environment therefore including also the societal and cultural contexts of such systems.
Therefore, socio-technical systems are considered as being structured around a technical core of physical artefacts which are enclosed and preserved by, and interact with comprehensive socio-historical and socio-institutional contexts (Ewertsson & Ingelstam, 2005; Hughes, 1983; Siddiqqi & Collins, 2017; Van der Vleuten, 2006). Ewertsson & Ingelstam (2005) highlight that especially the latter characteristic is fundamental in understanding these kinds of systems because it suggests that the technological component is shaped by its interaction with society through creation, adaption, and development. For this, Walker et al. (2008) formulated two main principles for socio-technical theory. First, the efficiency of a system is ascertained by the interaction between the social and technical components. Secondly, the optimalization of a single or individual component tends to increase an unpredictable, non-linear outcome of the system (Walker et al., 2008). These two principles capture comprehensively what Ropohl (1999) has coined as "*the reciprocal interrelationship between humans and machines (…) shaping both the technical and social conditions for work* (…)" (1999, p. 186). Accordingly, he (Ropohl, 1982) uses the socio-technical systems theory to describe both social and technical phenomena, "*the technization of society and socialization of technology*" (Ropohl, p. 191).
This aligns with the description of existing energy infrastructure system deeply rooted current [*energy and*] heat uses in the built environment as identified in **section 2.1**.

3.1.1 Energy infrastructure as socio-technical system

With systems theory describing "*a theory of interacting processes and the way they influence each other over time to permit the continuity of some larger whole*" (Sinnott & Rabin 2012, p. 412), different scholars from the school of thought of 'complex adaptive systems'(for example: Loorbach et al., 2017; Røpke, 2016) have distinguished different types of systems.

While Loorbach et al. (2017) differentiate between socio-institutional (e.g. education, labour), socio-ecological (e.g. fishery, forestry) and socio-technical systems (e.g. energy), Røpke (2016) distinguishes between resource and waste systems with an interaction between nature and society, distribution systems affecting the social provision of goods and services (e.g. tax system), geographical systems referring to different jurisdictional units (e.g. cities, regions), and [*socio-technical*] provision systems. The latter he describes as "*systems that transform energy [and resources] and render them useful for final consumption*." (Røpke 2016, p. 238). In terms of socio-technical [*provision*] systems an additional dimension has been attributed to the element 'social' since these systems provide crucial functions and end-use services to society (Geels, 2019; Loorbach et al., 2010).
With the energy infrastructure being defined as the totality consisting of generation or extraction, transport, distribution, trade and consumption of energy (Houwing et al., 2006) there are widely accepted as being conceived as socio-technical systems with highly interrelated components of technical and institutional nature that require both a comprehensive analysis and design (Bruijn & Herder, 2009; Chappin & van der Lei, 2014; Scholten & Künneke, 2016). This goes in line with Herder et al. (2018) highlighting that in analysing energy infrastructure it is important to acknowledge the interconnectedness of the social and physical network and its reciprocal influence. Loorbach et al. (2010) use the term 'infrastructure' to denote the physical components of the infrastructure, representing partly the parts of the totality of an energy system by Houwing et al. (2006). In figure 3 a schematic representation of a local gas infrastructure system, as this is the 'system' under study, is shown consisting of among others the high- and low-pressure network, gas distribution stations and delivery stations.

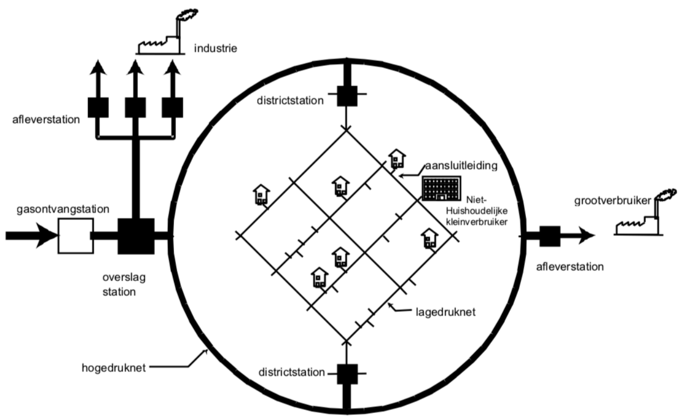

Figure 3: Schematic representation of the local gas infrastructure system (Source: Kiwa, 2017)

While the physical network can be defined as an '*ensembles of technical artifacts*' (Siddiqi & Collins 2017, p. 7) such as gas utilities (Verbong & Geels, 2009) the social network describes coevolutionary interactions between a variety of institutional factors such as [*energy*] policies, institutional frameworks and the strategies and behavioural practices of a broad range of actors such as utility companies, policy makers and end users (Bolton & Foxon, 2011; Foxon, 2011; Geels, 2005a). Existing energy systems are characterized by the alignment between the physical and social network (Geels et al., 2017), maintained by various technologies, policies, user patterns and among others cultural discourses (Geels, 2019). Therefore, evolution in these systems is gradually, characterized by path-dependency (Bolton & Foxon, 2011) and innovation in these systems is mostly incremental due to diverse lock-in mechanisms (Geels, 2019).

Gas infrastructure: an illustration of techno-economic lock-in mechanisms
With the terms techno-economic and technological lock-in mechanisms being used interchangeably, both describe the idea that '*as economic and cultural advantages accrue to existing incumbent technologies*, *barriers are created to the adoption of potentially superior or at least as valuable alternatives*' (Foxon 2013, p. 123). In relation to energy [*infrastructure*] systems, Foxon (2013) in line with Unruh (2000) highlights the fact that research is arguing that current high-carbon fossil-fuel based energy technologies are currently in a 'carbon lock-in' preventing the adoption of low-carbon alternatives. According to Kemfert et al. (2022) the continuing investments in the natural gas infrastructure as example for high-carbon fossil-fuel based energy technology poses a risk of delaying the renewable energy transition, as shown for the European energy system with an over-construction of conventional generation capacity becoming obsolete and underutilized soon (Löfler et al., 2019)
Geels (2019) identifies two major rationales behind the development of a techno-economic lock-in mechanism. First, sunk investment in infrastructure components such as pipelines or compressor stations create vested interest against transitional change (Geels, 2019). With infrastructure such as gas transport systems becoming more efficient when more users are connected to the grid, economics of scale can emerge when sunk investment in transport capacity are spread over an increasing area of distribution (Klitkou et al., 2015), for example the service area of a regional network provider. Due to their long technical lifespan and amortization periods, existing and new natural gas infrastructure assets run the risk of becoming stranded assets characterized by unanticipated or premature write-downs due to being rendered inoperative (Kemfert et al., 2022).
Secondly, decades of learning effects facilitate the development of high-performance and low-cost characteristics of existing energy technologies leading to incremental innovation (Geels, 2019). Regarding gas infrastructure such a learning effect can be identified in the switch from using grey cast iron to polyethylene (PE) used as pipeline material (Onderzoeksraad voor Veiligheid, 2009; Enexis Netbeheer, n.d.). While grey cast iron can be subject to embrittlement under certain circumstances (Callister & Rethwisch, 2015) for example through soil subsidence (Onderzoeksraad voor Veiligheid, 2009), PE is known for its high wear and low stiffness making them very suitable for the application as gas pipelines (KIWA, 2018). Such learning effects occur when knowledge, skills and organisation routines increase with cumulative production (Arthur, 1990). This development is comprehensively displayed in the historical development of the Dutch gas system (Correlje, 2011; Riemersma et al., 2020).
While Lindblom's incrementalism (Lindblom, 1959) might offer a useful lens to study [*energy*] infrastructure development (Silver, 2015), the switch from heating in the built environment based on natural gas combustion towards hydrogen combustion follows a rather non-linear development. Therefore, the following sections elaborates on transition theory including non-linear transitions in socio-technical systems.

3.2 Transition theory

With transition theory focusing on '*understanding radical systemic socio-technical changes. (…) change that goes beyond the ordering of the current system, which typically occurs over decadal time scales'* (Bergman et al. 2008, p. 2), the literature on transition theory highlights the interdependency of institutions [*as social component*] and infrastructures [*as physical component*] shaping societal systems with regard to energy technologies (Smith et al., 2005).

While different scholars have presented different definitions of the term transitions such as '*a shift from an initial dynamic equilibrium to a new equilibrium'* (Kemp & Rotmans 2005, p. 140) or '*transitions are transformation processes in which existing structures, (…) are broken down and new ones are established*' (Loorbach 2007, p.17), according to Rotmans et al. (2001) a transition has distinct peculiarities:

- It concerns large scale technological, economical, ecological, socio-cultural and institutional developments that influence and reinforce each other;
- It covers at least one generation and has therefore a long term nature;
- There are interactions between different scale levels (landscape, regime, nice).

While transitions are acknowledged as complex processes with a multitude of driving factors and impacts (Loorbach et al., 2008) and apply to societal complex systems (Loorbach 2007) such as the energy infrastructure system for among others the built environment (Verbong & Geels, 2010), transition theory is increasingly applied in understanding current problems of unsustainability and how more sustainable systems can be achieved (Elzen et al., 2004). Elzen et al. (2004) for example highlight the need for deep structural changes in the current energy system to address persistent and worsening environmental problems. The transition addressed in this study is the transition from the current (high carbon fossil-fuel based) heating system in the built environment to a sustainable hydrogen-based heating system [*in therefor appropriate areas*], captured as [*new*] stabilization in figure 4.

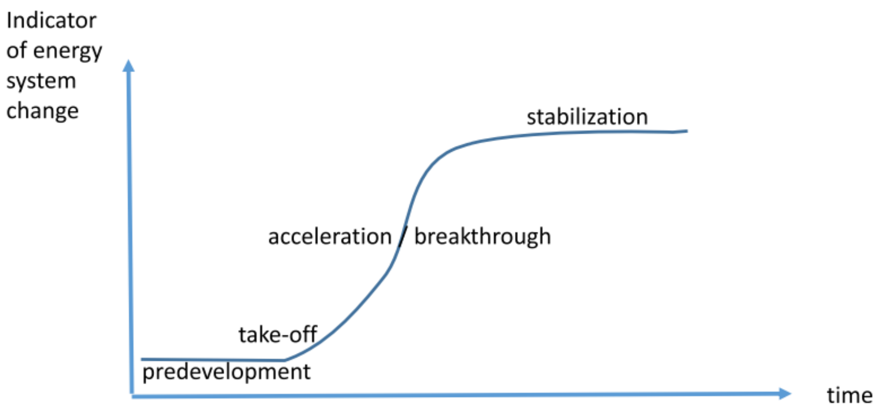

Figure 4: Four phases of transition (Orginal source: Rotmans et al., 2001)

Albeit transitions show a non-linear behaviour (De Roo, 2010), the transformation process of the system itself is a gradual one (Rotmans et al., 2001). According to Loorbach (2007) transitions can be characterised in terms of Schumpeter's (1934) 'creative destruction', where (prior) existing structures such as decentralized energy production based on biomass and coal faded away and got replaced by the large-scale centralized energy system based on Natural Gas and oil in the Dutch context (Loorbach et al., 2008).
The analysis of historical transitions, for example, in the Dutch energy system touched upon above (Loorbach et al., 2008) or in Dutch water management (Van der Brugge et al., 2005) suggest that transitions traverse four stages with divergent nature and speed of change in each stage (Rotmans et al., 2001). This process is represented by an S-shaped curve (figure 2). While the last two phases of a transition are characterized by structural changes visible through the accumulation of among others socio-cultural (acceptance) and technological changes (adaption of large-scale adaption of new technologies), and the stabilisation of a new dynamic equilibrium (Loorbach, 2007; Rotmans et al., 2001), these are currently absent for

hydrogen application in the built environment (Elbert, 2022; Gordon et al., 2022; McDowall, 2014). Therefore, only the first two phases of transitions with regard to hydrogen applications in the built environment are elaborated on.

- The predevelopment phase is characterized by little visible change on the societal level (Loorbach, 2007), the regime remains stable despite slow changes in the landscape (Rotmans et al., 2001). Nevertheless, there is increasing bottom-up innovation through experiments (Loorbach, 2007). Single buildings in an isolated and controlled environment are used for gathering experience with hydrogen applications for heating purposes and knowledge about repurposing processes [*from natural gas to hydrogen*], like in Uithoorn by the regional network operator Stedin (Stedin, 2021) or at the Green Village test location on the campus of the Technical University Delft (Wassink, 2021).
- During the take-off phase the process of change starts and the state of system begins to shift (Loorbach 2007; Rotmans et al., 2001), such as the move away from natural gas towards hydrogen for heating purposes in the energy supply system for the built environment. This phase is in need of an accumulation of experimental developments by different stakeholders (such as the increasing number of hydrogen pilot projects in the built environment by different regional network providers) supported by governmental subsidies and specific policy permits (Dutch: gedoog), like the temporal permit to transport hydrogen through existing gas infrastructure by the Authority for Consumers & Markets (ACM, 2022).

Socio-technical transitions

With section **3.1** and **3.2** describing the concepts of 'socio-technical systems' and 'transitions' considering energy infrastructure systems, in the following both concepts are brought together to discuss 'socio-technical transitions [*to sustainability*]'. Socio-technical transitions can be defined as the multi-dimensional shift from an initial stable socio-technical system to a new one involving changes in both the technological and social components of that system which are intrinsically linked (Geels, 2005b). While such transitions imply evolving technical and social aspects (Savaget & Acero, 2017), transitions can be understood as technological changes in a system transforming the way society functions (Geels, 2019; Nesari et al., 2022; Verbong & Geels, 2010). Such a transition initiated by a technological change in the energy infrastructure system was experienced by the Dutch society in the 20th century through the shift from traditional biomass and coal before the 20th century towards natural gas and oil for heating purposes (Loorbach et al., 2008). Therefore, the transition in an energy [*infrastructure*] system can be coined a socio-technical transition (Geels, 2019; Sovacool, 2016; Verbong & Geels, 2010)

While high rates of greenhouse gas emissions through natural gas combustion for heating purposes (Beccali, 2017) highlights what Grubler (2012) frantically formulated as '*the need for the next energy transition is widely apparent as current energy systems are simply unsustainable on all accounts of social, economic and environmental criteria'* (2012, p. 8), there is no standard or commonly accepted definition of an energy transition in the literature (Sovacool, 2016). Nevertheless, with an energy transition involving a change in an energy system like a particular energy carrier such as hydrogen (Gondal, 2019; Gordon et al., 2023), Melosi (2010) captures it comprehensively as '*the concept of energy transition is based on the notion that a single energy source, (…) dominated the market during a particular period or* *area, eventually by challenged and then replaced by another major source* (2010, p. 47). Turning to the application of hydrogen in the built environment for heating purposes as core topic of this research at this point, taking the optimistic attitude of recent academic insights about the possibility to repurpose natural gas infrastructure for hydrogen transport (Gondal, 2019; KIWA, 2018) into account, one could foresee a role of hydrogen as energy carrier in the current energy transition.

3.2.1 Multi-layer perspective

While transitions can be understood as the outcomes of alignments between developments at different levels (Geels & Schot, 2007), which was already coined by Rotmans et al. (2001) as 'interactions between different scale levels', researchers have highlighted the need for 'organisation-exceeding, qualitative innovations realised by different agents to change the current system (Bergman et al., 2008). So-called '*niches'* (Geels, 2005a; Geels, 2005b) emerge at the periphery of the existing socio-technical system (Geels, 2019).
With the transition towards a sustainable energy infrastructure system using hydrogen as energy carrier in the built environment can be framed as socio-technical transition, the multi-layer perspective (figure 5) originally developed by Kemp (Kemp & Rip, 1998, Geels & Kemp, 2000) can be used to conceptualise and analyse the different changes emerging on the multiple scale levels (Rotmans et al., 2001).

The multi-layer perspective (figure 5) distinguished '*three levels of heuristic, analytical concepts*' (Geels & Schoot 2007, p.399): socio-technical landscape, socio-technical regimes and socio-technical niches (Geels, 2002). While the niche level is elaborated on below, the landscape and regime level are described in box 1.

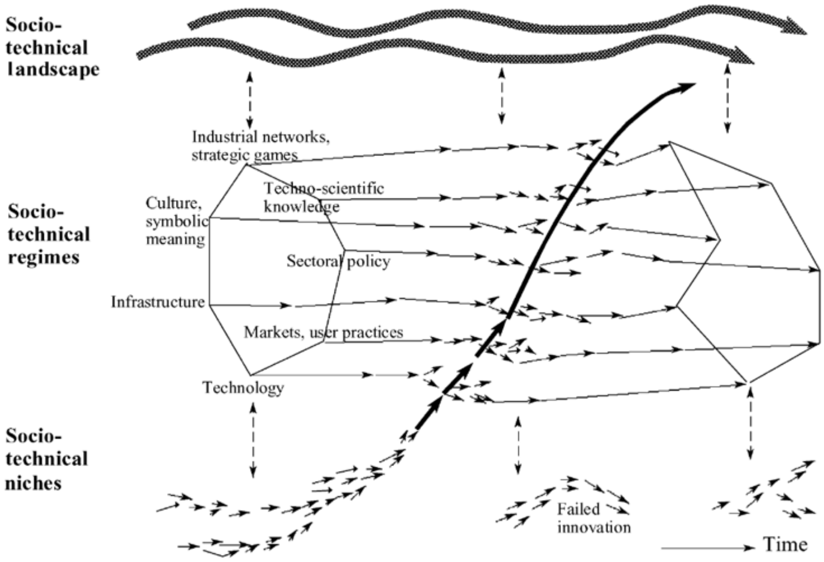

Figure 5: Multi-layer interactions (Source: Geels & Kemp, 2000)

BOX 1: Landscape and regime level of the multi-layer perspective

Landscape level

The developments of and interactions between niche-innovations and existing socio-technical [*energy*] systems are influenced by the landscape level (Geels, 2019). This wider context includes slow changing world views and paradigms, or material infrastructure (Bergman et al., 2008; Geels & Schoot, 2007) wherein the energy transition of the built environment takes place (Geels, 2019). With currently accounting for more than 90% of the heat provision for the built environment combustion of natural gas can be seen as the current energy paradigm (Bekkers, 2019). With the landscape forming an exogenous environment beyond the direct influence of regime and niche actors, changes take place slowly (Geels & Schoot, 2007). Despite only small decreases in national consumption of natural gas (from around 8.814 million cubic meters 'Gronings Gas' in 2013 to around 7.961 million cubic meters in 2020) (RVO, 2021), macro-political developments such as the Paris Agreement (United Nations, 2015), the European Green Deal (European Commission, n.d.) or the Dutch climate agreement (Klimaatakkoord 2019) can be identified as sustainable harbingers towards a climate-neutral system.

Regime level

The socio-technical regime refers to shared cognitive routines (Geels & Schoot, 2007), perceptions and actions of different groups such as incumbent actors, policymakers and regulations, and users (Geels, 2019). Cultures and practices dominant within the current system, as well as the above-discussed technological lock-ins (**section 3.1.1**), hold the existing regime intact. With striving for optimizing the current system (Rotmans et al, 2001) strategies by governmental, non-governmental and semi-governmental institutions (such as regional network providers) are '*focused on optimisation and protecting investments rather than system innovation*' (Van der Brugge et al. 2005, p. 167). Energy infrastructure like gas pipelines have a technical lifetime of several decades (Kemfert al., 2022) and is still being replaced in the local Dutch context (Enexis Netbeheer, n.d.; Stedin, n.d.). With the legal protection of property, the decommissioning of infrastructure assets after a fraction of its lifetime poses great challenges (Serkin & Vandenbergh, 2018) adding to further stabilisation of the current regime.

Niche level

Niches form '*protected spaces'* (Geels 2019, p.190) protecting innovations from existing market sections and mature learning processes (Geels, 2019). Niche-innovations technological [*or social*] by nature are developed by small networks or dedicated actors (Geels, 2002). While the degree of radicality of a niche-innovation depends on how much it deviates from the existing system on technical or infrastructural dimensions (Geels, 2019), in how much the local practice of the innovation differing from the current regime factors in as well (Bergman et al., 2008). Following Geels (2019) argument on infra-structural innovations the injection of alternative energy carriers in reconfigured gas grids can be considered as a niche-innovation. When considering the combustion of natural gas as the predominant

market section in heating the built environment (Bekkers, 2019), the application of hydrogen as energy carrier in the built environment can be regarded as niche-innovation (Smit et al., 2007) since this is done exclusively in pilot-project environments, carried out by regional network providers (ACM, 2022; SodM, 2022).
In order to facilitate the further application of hydrogen as niche innovation in the built environment, ways have to be identified that promote the rollout on a larger scale. Therefore, the next section discusses repurposing strategies of existing gas transport infrastructure in light of the waste management hierarchy.

3.3. Waste management strategies

With gas pipelines and other energy infrastructure components having a technical lifespan of several decades (Kemfert et al., 2022), coupled with high capital investment cost resulting in irreversible design decisions (Herder et al., 2011) the repurposing of existing energy infrastructure can play an important role in the reduction of decommissioning of old infrastructure (Invernizzi et al., 2020) and the costly construction of new one (Kemfert et al., 2022). While Invernizzi et al. (2020) describe decommissioning as a '*suite of processes involved in withdrawing a facility from service at the end of its life; its deconstruction and dismantling; and the removal of components for reuse*' (2020, p. 111676), policies and experience are limited within the energy infrastructure sector to perform this due to a historical focus on the planning and design of new infrastructure instead of the decommissioning of it (Invernizzi et al., 2019).
While the Waste Framework Directive (WFD) of the European Union concerned with '*measures to protect the environment and human health by preventing or reducing adverse impacts of the generation and management of waste by reducing overall impacts if resource use*' (European Parliament 2008, p. 2) addresses waste management in general, it contains an important and prominent Dutch contribution about the waste hierarchy (Villoria Saez, 2011). The waste management hierarchy, also called 'Ladder of Lansink' due to its founder the Dutch politician Ad Lansink in 1979, describes an order of preference for waste management and resource conservation options (Zhang et al., 2022). The hierarchy (figure 6), considering an order of waste management following a five-step pyramid with 'prevention' as the most preferred option and 'disposal' as the least preferred option (Zhang et al., 2022), has as goal to improve the effectiveness of waste treatment by reducing environmental impacts and mitigating resources depletion (Williams, 2015).

Based on the general waste management hierarchy by Lansink (European Parliament, 2008) context-specific waste hierarchies have been adapted tailored different waste categories or treatment efficiencies (Laurent et al., 2014). With construction and demolition waste (CDW) of among others energy infrastructure being one of the largest waste streams in the EU accounting for more than a third of all waste generated in the EU (European Commission, n.d.), Hendricks and Dordthorst (2001) introduced the 'Delft Ladder'. The contribution of the Delft Ladder is found in the specification of the 'reuse' step into: construction reuse, element reuse and material use depending on life cycle analysis of a construction (Hendricks & Dordthorst, 2001). While the context of this study is the potential reuse of existing gas infrastructure for hydrogen transport, the remaining section focuses on the 'reuse' step.

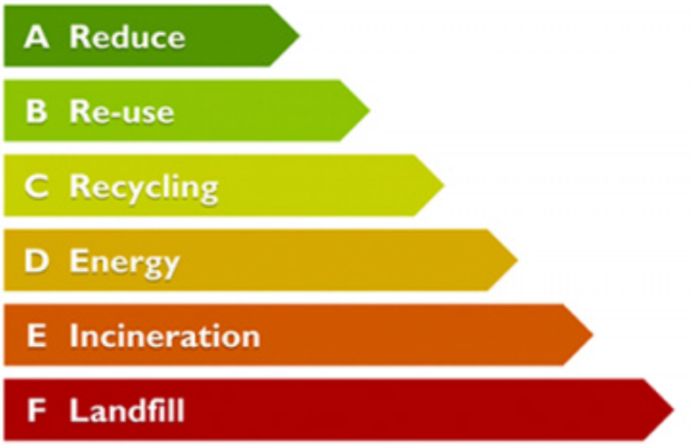

Figure 6: Waste management hierarchy by Lansink (Source: van Meerbeek, 2015)

3.3.1 Reuse in waste management

While the term 'reuse' must be defined context-specific depending on the sector of interest, in general it can be described as the process in which discarded components are recirculated and sometimes upgraded according to the material structure and used for the same function without destruction (Cooper and Allwood, 2012). Despite reuse components may require only minor reprocessing (Iacovidou & Purnell, 2016), the reuse might be limited by the lack of confidence in the structural properties or performance of reused components (Allwood et al., 2011). Following Iacovidou & Purnell (2016) a clear demonstration of the technical feasibility is needed to unlock the reuse potential, which is influenced by the type and quality of material/component, its durability, fatigue loading and projected lifetime (Dorsthorst & Kowalycyk, 2005). These factors go in line with originally proposed aspects of the reuse possibilities by Hendriks & Dorthorst (2001) for the construction level: technical state of the construction (remaining lifetime), possibilities to improve current technical state (by repairing or retouching) and the flexibility of the construction.

In the context of reuse of energy infrastructure, especially for gas transport networks, Banet (2022) proposes the addition of sub step 'repurposing'. While according to her reuse entails the use of existing infrastructure with the same purpose, repurposing entails the reuse of installation and infrastructure for a different purpose such as the use of gas infrastructure for the transport of hydrogen as energy carrier. This goes in line with what the DNV (Aarnes & Monsma, 2021) writes in their white paper about utilising existing onshore infrastructure for scaling hydrogen projects. With the repurpose of existing gas network assets being a key aspect of emerging hydrogen gas networks (Speirs et al., 2018) the decarbonisation of existing gas networks can play an important role in future energy systems (Dodds & McDowall, 2013). The next section will therefore discuss the suitability of existing gas transport grids for hydrogen transport in the local context, given the scope of this research.

Suitability of the local gas grid for hydrogen transport

The transportation of hydrogen gas through existing gas transport infrastructure demands certain considerations regarding material and operational conditions (Kouchachvilli & Entchev, 2018; Schoots et al., 2011). While local gas distribution systems are deemed to be the least problematic link in the value chain [*when considering the total gas infrastructure system for a moment*] due to their low operating pressure and the large-scale use of

polyethylene pipes (Quintino et al., 2021), specifically in the Dutch context (KIWA, 2018; KIWA, 2019; Enexis, n.d.; Liander, n.d.), leakage [*detection*] is the most important issue to consider (Gondal, 2019). This goes in line with the findings of the KIWA-report (2018) about future-proof gas distribution networks that highlight the risk of permeation being five times higher for hydrogen as for methane (CH4 = natural gas) when considering synthetic material (*Dutch: kunststoffen*). However, for current systems [*mostly made from PE in the Dutch local system*] leakage should be manageable (Quintino et al., 2021) with an estimated leakage under 0.001% of the total transported gas in the context of hydrogen (Scholten & Wolters, 2002).
The most important plastics that occur in the [*Dutch*] gas distribution networks are the three generations of PE (polyethylene), hard and impact-resistant PVC, the rubbers NBR and SBR, and the plastic polyoxymethylene (POM) (KIWA, 2018). While this applies mostly for pipe materials (KIWA, 2018), also rubbers used for seals in connections and valves (KIWA, 2018) and parts of pressure regulators are partly made from these materials (Quintino et al., 2021). Different types of plastic can be affected through both chemical reactions with hydrogen or because their physical characteristics change through absorption of hydrogen (Bauer et al., 2016; KIWA, 2018). While the sensitivity of the material is dependent on different factors [*which go beyond the scope of this research*], it can be concluded that the most common plastics and rubbers used in existing local gas distribution network don't show any degradation due to hydrogen (Bruin et al., 2015; Hermkens et al., 2018; KIWA, 2018; Melaina et al., 2013). However, it is suggested to test in particularly fittings, sealants and connectors on a case-by-case basis (Klopčič et al., 2022; Quintino et al., 2021).
When considering operating conditions for hydrogen transport, district stations on the local scale have been identified as potential bottlenecks due to the lower energy density expressed in the calorific value kWh/m3 (Quintino et al., 2021; Schoots et al., 2011). The energy density, being the amount of energy stored in a unit volume, is approximately three times lower for hydrogen than for natural gas considering the same temperature and pressure conditions (Mischner, 2021). Therefore, in order to transport the same amount of energy [*for heating purposes in the built environment*] using hydrogen as energy carrier requires three times the amount of gas transported through the local pipes (KIWA, 2018) Theoretical this seems possible, because the lower density of hydrogen (Mischner, 2021) enables transport of approximately 80% of the energy capacity through pipes with equal diameter and pressure drop (Haeseldonckx & D'haeseleer, 2007). However, this requires an increase in flow rate to maintain a stable energy supply (Klopčič et al., 2022; Quintino et al., 2021). Oscillation and corresponding noise are potential negative effects that need further investigation in practical settings (Klopčič et al., 2022; KIWA; 2019).

3.3.2 Repurposing of natural gas infrastructure

Taking the goal of the Dutch government being climate-neutral in 2050 (Klimaatakkoord, 2019), implying for the built environment the phasing out of high-carbon energy carriers (in particular natural gas) for heating applications (Rijksoverheid, n.d. b), into account a major challenge in the energy transition is the provision of sustainable heating for households (Weeda & Segers, 2020). Next to the introduction of new energy infrastructure the sustainable use of old infrastructure can cater for a strong boost to the energy transition (Invernizzi et al., 2020). While the repurposing of existing energy infrastructure is subject to diverse uncertainties (Enagás et al., 2020), the Dutch Transmission System Operator (TSO), in

particular the Gasunie being responsible for gas transmission (Gasunie, n.d), expects the repurposing of existing natural gas pipelines for hydrogen transport (Gasunie & Tennet, 2019). Also on the local scale, where the regional network providers are responsible, strategies and implementation plans for repurposing [*parts of*] the local gas grid are drawn up (Enexis Netbeheer, n.d.; Liander, n.d.; Stedin, 2018).
However, this is not a self-developing process due to the complexity inherent to the switch from natural gas to hydrogen as energy carrier. Therefore, it might call for well-considered decision-making, time and spatial context dependent.

3.4 Decision-making in spatial contexts

Spatial decisions are made by individuals on a regular basis, in both personal or professional matter: what route to take to the weekly farmers market visit, where to hold the start-up meeting for the new research project from work, or on which roof to put on solar panels first. Selecting an alternative usually requires a trade-off between different considerations. Therefore, spatial decision making involves a large variety of feasible alternatives and multiple, conflicting and disproportionate evaluation criteria (Malczewski, 2006). Since individuals are characterized by different preferences with regard to the relative importance of certain criteria and apply different values to them, a variation of decisions can be the outcome (Greene et al., 2011). With an increasing degree of complexity and importance, the need for a formalised decision-making process with transparency about the rationale behind the decision is growing as well (ibid). In order to make a well considerd decision one needs to grasp the problem leading to the decision, define the need and purpose of the decision, lay-out the assumptions and criteria relevant for the decision, map the stakeholders involved in the decision, determine the groups affected by that decision and outline the alternative actions to take. The ultimate goal of the decision-making process is then to determine the best or most suitable alternative or to prioritize [*for example*] resource allocation (Saaty, 2008). One way of approaching complex decision making is the use of structured approach, like an analysis that is able to take account multiple criteria.

3.4.1 Multi-criteria decision analysis

Multi-criteria decision analysis (MCDA) can be defined as '*a collection of formal approaches which seek to take explicit account of [key factors] in helping individuals or groups explore decisions that matter*' (Belton & Stewart 2002, p. 2). The MCDA-approach helps decision makers in analysing possible actions or alternatives based on a variety of incommensurable factors or criteria, applying depending on the particular method different decision rules to rate those criteria or rank the alternatives (Eastman, 2009; Figueira et al., 2005; Malczewski, 2006). While the criteria or factors influencing the ultimate decision typically can't be maximized or be defined comprehensively, the main focus is on electing and making the values and subjectivity applied to the more objective measurements transparent, and understanding the implications (Belton & Stewart, 2002; Roy, 2005).
Due to the huge diversity of different MCDA methods, selecting the appropriate method or combination of methods depends on the context of the decision, the available time frame and the level of experience of the researcher amongst other factors (Greene et al., 2011). Nevertheless, a clear separation of methods can be based on if there is one or multiple objectives. In a context of a single decision objective, multi-criteria decision making (MCDA) is required according to Eastman (2009) and Malczewski (1999).

Analytic hierarchy process

The process of decision making, choosing the 'most suitable' option from a variety of possible alternatives, involves many criteria and potentially sub-criteria to rank the alternatives of that decision (Saaty, 2008). According to Saaty (2008) there are two possible routes to obtain knowledge about something or anything. Through this, the same holds true for doing a multi-criteria analysis, namely two possible ways to perform such an analysis (Chandio et al., 2013). Firstly, it is possible to study an object in itself to such an extent that its various properties become clear, synthesize these findings and draw conclusions in this way. The second way is to study the object in relation to other similar entities and relate it to them through comparisons (Saaty, 2008; Chandio et al., 2013). In order to make comparisons, a scale of numbers is needed that indicates how many times more important or dominant one factor over another factor is with respect to the decision goal they are compared for (Saaty, 2008).

The analytical hierarchy process (AHP) is an analysis approach of '*measurement through pairwise comparisons and relies on the judgments of experts to derive priority scales'* (Saaty 2008, p. 1). Through its three main objectives – structuring complexity, measurement, and synthesis – the hierarchical structure of the AHP approach makes measuring and synthesizing a variation of factors within a complex decision-making process possible, enabling the combination of parts in a whole a simpler manner (Russo & Camanho, 2015). The general purpose of the AHP approach is seeking a systematic practice assisting decision makers in selecting the 'best' alternative from a variety of possible options under the presence of [*all the different*] factors identified that affect the decision (Chandio et al., 2013; Russo & Camanho, 2015). A decomposition of the decision in a number of steps is needed to make a decision in an organised way generating priorities (Saaty, 2008). The methodology (see **section 4.2.4**) of this study elaborates further on this.

3.4.2 GIS-based multi-criteria decision analysis

A Geographical information system (GIS) has the potential of being a powerful tool in spatial modelling (Klosterman, 1995; Yaakup et al., 2004) involving among others a huge variety of spatial decision challenges (Malczewaski, 2006) with alternative scenarios in the form of maps (Ludin & Yaakup, 2006). Since its origin in the 1970s, the GIS technology has been developed towards the distinct capability of automating and analysing huge amounts of varied spatial data. Therefore, GIS is acknowledged '*as a decision support system involving the integration of spatially referenced data in a problem-solving environment'* (Cowen 1988, p. 1552). The integration of the GIS tool and the MCDA has the ability of providing a useful and exclusive solution in dealing with problems associated with analysing spatial decision problems (Vaidya & Kumar, 2006). The underlying purpose of the spatialised application of MCDA is to complement the traditional question of '*what'* with the augmented question of '*where'* (Malczewski, 1999). The GIS-based MCDA is increasingly used in land suitability analysis and other various contexts of spatial decision problems (Chandio et al., 2013). These techniques are useful to spatial planners, engineers, or decision makers to provide a decision-making framework for energy landscape planning as exampled in the literature (Messaoudi et al., 2019; Zubaryeva et al., 2011). With area suitability dealing with large spatial data sets and involving multiple factors/criteria, the analytical hierarchy process enables approaching the decision for site selection in a systematic way (Mohit & Ali, 2006). Through the provision of a decision-making framework the AHP integrated in GIS deals with the spatial analysis of the relative suitability of land (Mendoza, 1997).

Application in energy related planning issues

Recently the academic literature has been seeing an increasing number of articles published in the field of energy related planning issues using a GIS-based multi-criteria decision analysis (see for example: Ajanaku et al., 2022: Asanza et al., 2021; Dehshiri & Deshiri, 2022; Messaoudi et al., 2019). While a variety of MCDA-methods exist, it is acknowledged that the AHP-methodology represents one of the most used approaches on sustainable energy planning (Vasileiou et al., 2017), within among others the application on suitable site selection for hydrogen projects (Messaoudi et al., 2019; Wu et al., 2021; Taoufik & Fekri, 2023). Giving the complexity inherent to the process of determining suitable areas for the application of hydrogen in the built environment involving multiple aspects of spatial, environmental, or technical nature (Ma et al., 2005) the AHP-methodology is deemed as suitable in the context of this research.

3.5 Conceptual framework

In the previous sections (including **chapter 2**), a set of concepts and theories relevant for an understanding of decision-making in the context of socio-technical system transition were discussed. A short overview is provided below:

- Section **2.1 - 2.3**: Introduction to hydrogen as energy carrier and its application in the built environment
- Section **2.3**: Hydrogen in the Dutch heat transition
- Section **3.1**: Gas distribution infrastructure as socio-technical energy system
- Section **3.2**: Transition theory and multi-layer perspective: hydrogen as niche development in the take-off phase
- Section **3.3**: Waste management hierarchy: repurposing existing gas transport infrastructure for hydrogen transport
- Section **3.4**: Decision-making in spatial contexts relating to sustainable energy landscape planning

The conceptual model (figure 7) gives an overview of the concepts that are expected to be related to each other in the context of the application of hydrogen as energy carrier in the Dutch heat transition. Based on the literature, it can be expected that between [*the position of*] hydrogen as energy carrier in the built environment and [*the potential of*] repurposing existing gas infrastructure exists a reciprocal relationship (H1), with the application of hydrogen in certain neighbourhoods increasing the likelihood for repurposing the existing gas distribution network and with the validation of the technical fitness of existing gas infrastructure transporting hydrogen strengthen the position of hydrogen as energy carrier in the built environment. Since hydrogen as energy carrier through its potential of delivering high-temperature heating as well as repurposing strategies through its potential to contribute to the development of a (future) hydrogen network are acknowledged to play a role in the Dutch heat transition, both are expected to influence the development of a multi-criteria decision analysis in the context of spatial allocation of hydrogen as energy carrier (H2a/H2b). Lastly, the identification of suitable locations for the application of hydrogen through a multi-criteria decision analysis is expected to contribute to [*a*] socio-technical transition in [*the*] energy infrastructure system (H3).

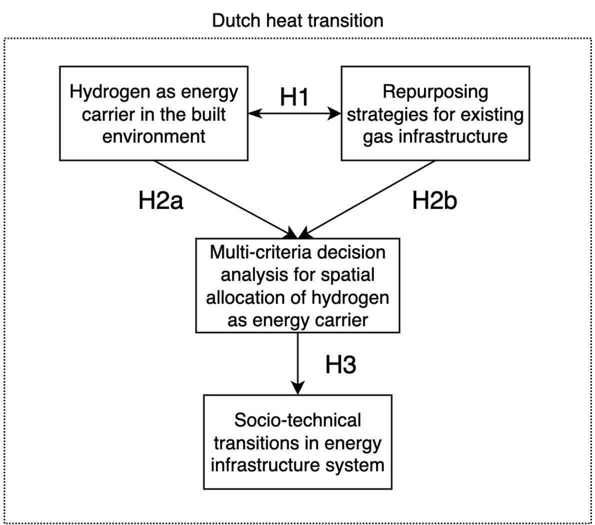

Figure 7: Conceptual model

4. Methodology

This chapter elaborates on the research design and the corresponding methods that are used within this study to collect and analyse data (**section 4.1**). **Section 4.2** elaborates on the different data collection techniques, provides an anonymized list of the interview respondents as well as the participants of the focus groups. The methods used to analyse the primary and secondary data are described in **section 4.3**. Finally, the ethical issues related to this study are discussed (**section 4.4**).

4.1 Research design

This explorative research, characterized by making a tentative first analysis of a new topic (Swedberg, 2020), was deployed to develop a decision-making model. With qualitative (which relevant criteria; technical feasibility of hydrogen transport in current local gas infrastructure) and quantitative (assigning weights to criteria; spatial demarcation) aspects being part of the main research question, a mixed-method approach is considered suitable (Tashakkori & Creswel, 2007). According to Johnson & Onwuegbuzie (2004) mixed-method research has the ability to '*combine methods in a way that achieves complementary strengths and non-overlapping weaknesses*' (p. 18) in order to learn more about a certain research topic (Creswell & Plano Clark, 2007). Furthermore, the triangulation approach [*using different data collection techniques*] is used to increase the credibility and validity of this study.

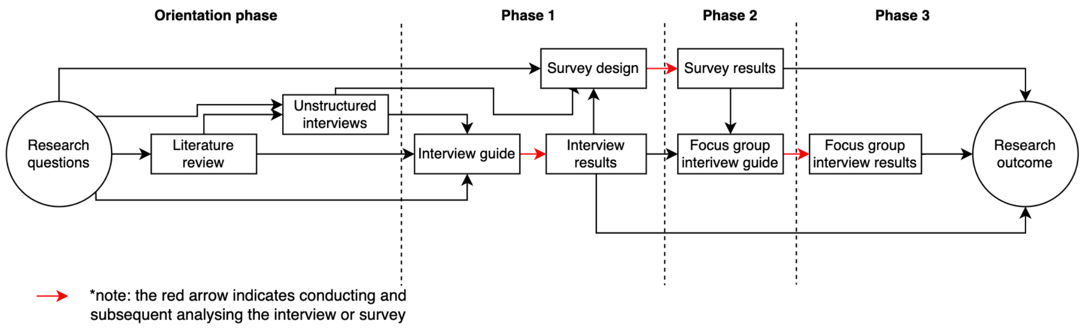

Figure 8: Schematic overview of research design

Figure 8 shows a schematic overview of the research design, consisting of four consecutive phases. The sequence of methodological steps taken here follows an increasing level of detail and demarcation towards the achievement of the main research objective, namely the development of a decision-making model. Due to the scientific novelty of this research topic, based on the combination of research question and methods (Luo et al., 2022), the orientation phase of this study entailed a literature review and a couple of unstructured interviews with researchers and consultants within the field of hydrogen applications [*in the built environment*] to determine an appropriate research strategy and to legitimize the subsequent methodological choices. Furthermore, especially the unstructured interviews provided input for the interview guide that is used for semi-structured interviews.During the first phase of data collection semi-structured expert interviews have been conducted to give answers to sub-questions 1, 2 and 3, and to provide input for the questionnaire design. In data collection phase 2 a questionnaire has been set out to answer sub-question four. Next to that, the survey results together with the interview results formed the basis for the focus group guide. A focus group in phase 3 helped to answer sub-questions 4 and 5, and to synthesize all results to answer the main research question.

Development of decision-making model

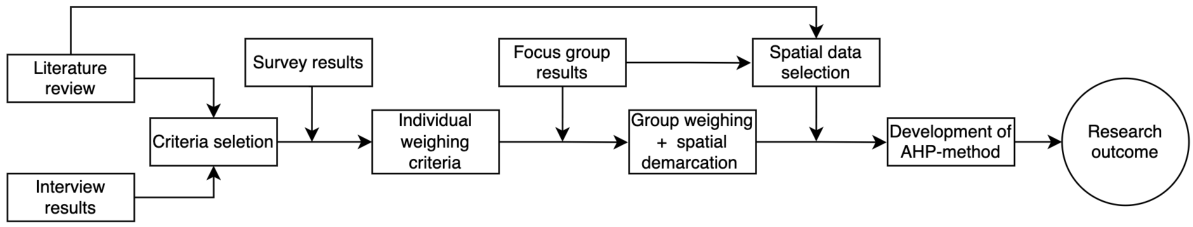

Figure 9: Schematic flowchart of development of decision-making model

While figure 8 shows a schematic overview of the research design containing the methodological steps taken in this research, figure 9 represents a schematic overview of the different steps taken towards the development the decision-making model [*for the neighbourhood prioritization*].

The interview results together with supporting literature review led to the criteria selection (corresponding with the objective of the third sub-question). The survey results led to a first [*conceptual*] criteria weighing done by the different survey respondents individually (corresponding with the objective of the fourth sub-question). During the focus group the spatial demarcation of the criteria has been discussed, followed by an individual pairwise comparison by the experts.

Units of analysis

The unit of analysis is determined by defining a spatial boundary, theoretical scope and timeframe (Yin, 2015). While the spatial boundary of this research is defined by focusing on the Dutch context, the theoretical scope is defined by both literature review and expert opinion based on interviews. The data collection period [*ranging from 02.2023 – 06.2023*] defined the specific time boundaries of this research.

4.2 Data collection

Box 2: Unstructured interviews

Given the content-related novelty of this study [*in particular the identification of a neighbourhood prioritisation suitable for the application of hydrogen as energy carrier*] (see **section 1.4** for elaboration on the knowledge gap), in total six unstructured interviews with experts [with different academic and practical backgrounds] have been consulted on various topics during the research process. With Minichiello et al. (1990) describing unstructured interviews as '*interviews in which neither the question nor the answer categories are predetermined*' (1990, p. 1), this applies well in the context of this study where the researcher despite having a general idea about the overall topic of the conversation, questions were not predetermined but emerged along the conversation. While most of the interviews (1, 2 and 3) were used as food for thought to inform the semi-structured interviews and literature review, interview 4 was used to discuss a certain criterion (social acceptance) in preparation of the survey design, in two interviews (5 and 6) the set-up and conducting of the focus group were discussed and interview 6 was utilized to discuss and prepare suitable data sets for the focus group. In appendix 4.1 an overview of the unstructured interview respondents can be found.

4.2.1 Semi-structured interviews

With interviews being one of the most prominent data collection tool (Punch, 2014), it is recognized as a suitable way of accessing people's perceptions, definitions of situations and constructions of reality (Patton, 2002). Depending on the research context and objectives, the researcher's prior knowledge from the topic and the experience of the researcher a certain typology of interview should be used (Minichiello et al., 1990). In this research, it was chosen to use semi-structured interviews without a pre-defined list of questions which gives room for the respondents to bring in own topics and ideas corresponding to the overall research theme (Reulink & Lindeman, 2005). Nevertheless, to guide the interview and conceptualize the input, an overview of discussion points was drafted and sent to the respondent beforehand. The research objectives outlined in chapter 1, the theoretical framework in chapter 2 and 3, and the unstructured interviews in the orientation phase guided the construction of the interview guide. Fielding (1996) highlights the importance of using the research objectives and literature review as a guideline for drawing up the interview topics and questions to ensure that relevant data for answering the main research questions is gathered. The interview guides can be found in appendix 4.2.On the other side, it is important to carefully consider suitable participants for the interviews (Clifford et al., 2010) and that the selection should be based on their experience and knowledge regarding the research topic [*in this case the application of hydrogen as energy carrier in the built environment*] (Longhurst, 2016). The selection of respondents was done based on involvement with hydrogen pilot projects [*in the built environment*], on recommendations resulting from the unstructured interviews, and based on personal interest in the more technical site of the heat transition. As the majority of interview respondents were employees from regional network operators.
Respondents were approached via email or telephone to make an appointment for the interview. All interviews have been conducted via Microsoft Teams, except for two. While one interview took place at the municipality of Groningen, the other face-to-face interview took place at the pilot project location in *********** (***********) including a guided tour over the premises.

Table 4.1: Overview of interview respondents

#	Name of respondent	Organisation	Function	Date	Place
I1	*************	*****	Project manager Hydrogen pilot	2-03-23	Online
I2	*************	*****	Asset manager	2-03-23	Online
I3	*************	*****	Program manager	2-03-23	Online
I4	*************	*****	Innovation manager	3-03-23	On-side*
I5	*************	*****	Asset manager	16-03-23	Online
I6	*************	*****	Program consultant**	9-03-23	Online
I7	*************	*****	Asset manager	20-03-23	Online
I8	*************	*****	Project manager Hydrogen pilot	21-03-23	Online
I9	*************	*****	Project manager Hydrogen pilot	8-03-23	Online
I10	*************	*****	Program manager Energy	13-03-23	Groningen

*On side at hydrogen test location of network provider ******* in *******, ******* (NL) (see appendix 4.3 for the excursion journal)
**for Energy and Heat in the Built Environment

Data saturation
With data saturation being 'identified' as the point in research where sufficient data has been collected to draw meaningful conclusions and further data collection [*employing a specific tool such as interviews*] will not produce value-added insights (Saunders et al., 2018), Fusch and Ness (2015) claim that *"failure to reach saturation has an impact on the quality of research conducted."* (2015, p.1408). While for qualitative studies general guidelines on how many interviews should be conducted exist (Majid et al., 2018) with for example five to 25 (Creswell, 2009) or up to 12 (Guest et al., 2006), Kumar (2005) highlights that the number of participants is not the primary concern but rather ensuring data saturation depending on the depth of the data. Considering the specific technical-spatial perspective of this research focussing on the technical side of the heat transition and hydrogen's potential position in it, the research has chosen for interview participants from a rather homogenous group (with seven of the ten respondents from a reginal network provider). According to Kuzel (1992) six to eight interviews are sufficient for such a context. After in total ten semi-structured interviews the researcher was convinced of having reached data saturation in terms of relevant criteria on the local level [*informing a decision-making model*] and therefore decided to continue with designing the questionnaire (**section 4.2.2**) and analysing the interview transcripts (**section 4.3.1**), also considering the limited time frame of this research.

4.2.2 Questionnaire
Survey research is particularly useful for gathering people's opinions about certain issues. While each survey is meant for a unique topic in a unique population, the process of designing and distributing involves a common set of points of attention (Clifford et al., 2010). First, the survey design should be tailor-made to fit the research project at hand, including a proper explanation of the research objective and clear and effective questions (Groves et al., 2009). Secondly, the survey needs to be distributed in a way suitable for the respondents. Thirdly, the research population receiving the survey in terms of knowledge about the topic and capabilities of understanding the questions needs to be in line with the research objective (Clifford et al., 2010).
The survey for this research has been designed using the software Qualtrics XM provided via a university license of the University of Groningen. The survey design consisted of two blocks of questions. First, multiple-choice and open questions gathered personal information of the respondent. Secondly, a matrix table question was used to perform pairwise comparisons of the seven relevant criteria identified during the interviews. Here a 9-point Likert-scale was used as fixed-response options. The advantage of fixed-response questions is that they are relatively easy to analyse as all responses are similar (Clifford et al., 2010).
The survey was distributed by e-mail to all interview respondents with explanation in the mail and the offer to get in contact with the researcher if additional explanation is needed. Because prior knowledge of the research objective was needed to fill in the survey, only interview respondents have been approached. The survey was active from April 18th till May 20, 2023. An overview of all survey-questions can be found in appendix 4.4.

4.2.3 Focus group

With the terms 'group interview' and 'focus group [*interview*]' being used interchangeably, the terms describe a situation where the researcher works with several respondents at the same time instead of just one (Punch, 2014; Wilkinson, 2004). Instead of a traditional process of alternating questions and answers as with a normal interview, the focus group is directed by open questions and topics supplied by the researcher (Merton et al., 1990). Furthermore, the role of the researcher changes more towards a moderator and facilitator (Punch, 2014) guiding the group interaction along pre-defined topics. Morgan (1988) highlights that '*the hallmark of focus groups is the explicit use of the group interaction to produce data and insights that would be less accessible without the interaction'* (p. 12). This goes in line with the findings of Krueger & Casey (2000) stating that the focus group environment is helpful for participants to discuss new ideas and [*sometimes*] conflicting opinions and thoughts. In mixed methods research focus groups can be used to deepen and discuss results surveyed (Punch, 2014).

In this research the focus group has been used to discuss the results from the survey, where the respondents were asked to perform a series of pairwise comparisons (see section 4.3.3), and to further elaborate on the spatial demarcation of the set of relevant criteria. A more detailed overview of the focus group topics and corresponding questions can be found in appendix 4.5.

Willingness for participation in the focus group was asked in the last question of the survey. Additionally, all interview (therefore potential survey) respondents have been approached via mail one and two weeks after the survey has been sent out. Due to the complexity of the research objective, it has been chosen for approaching only respondents from prior data collection methods (interviews/survey). Therefore, most of the focus group respondents were employees from regional network operators. The focus group has been held online, using Microsoft Teams on 31 June 2023.

Table 4.2: Overview of focus group participants

#	Name of respondent	Organisation	Involvement hydrogen project
G1	********	*****	Hydrogen research
G2	********	*****	Neighbourhood pilot project
G3	********	*****	Neighbourhood pilot project
G4	********	*****	Neighbourhood pilot project

4.2.4 Multi-criteria decision analysis - AHP approach

While the theoretical framework of this study (see **section 3.4**) elaborated on the origin, background, fields of applications and suitability in energy planning related research of the MCDA AHP-approach already, here the usage instruction of the tool is elaborated on. In order to make a decision in an organised way generating priorities a decomposition of the decision in several steps is needed (Saaty, 2008). With more than 13.500 citations in total and about 580 citations still in this year (2023), the article by Saaty (2008) and its AHP-method can be considered as a valuable contribution to the field of decision-making with great legitimacy [*given the high citation impact*].

While Saaty himself (2008) originally defined four steps different scholars (see for example: Chandio et al., 2013; Russo & Camanho, 2015 or Haller et al., 1996) made valuable extensions.

The following steps are part of the AHP-method:

1. Defining the problem and determining the relevant knowledge sought (Saaty, 2008). In this step Russo & Camanho (2015) highlight the importance of making explicit all assumptions and perspective by which the decision has been taken.
2. Saaty describes the second step as "*structuring of the decision hierarchy from the top with the goal of the decision, then the objectives from a broad perspective through the intermediate levels towards the lowest level being the possible alternatives*" (2008, p. 85). In this research the main goal is the development of a neighbourhood prioritization, while the objectives are different relevant criteria influencing this main goal and the alternatives on the lowest level are all the neighbourhoods not deemed suitable for a district heating or all-electric solution. Haller et al. (1996) stress the necessity of an extensive enough hierarchy while at the same time eliminating non-relevant criteria.
3. Construct matrices of pairwise comparison (Saaty, 2008). A verbal scale ranging from 'equal important' (number 1) to 'extreme important' (number 9) is used for the comparison to show '*how many times more important or dominant one element is over another element with respect to the criterion to which they are compared to*' (Saaty 2008, p. 85). Figure 10 shows the verbal scale. Depending on the research topic, the completion of the pairwise comparison is done by experts (Russo & Camanho, 2015). The matrix used in this study is displaced in section 4.3.5.
4. Calculating the relative weight of each criterium in the hierarchy (Saaty, 2008). Section 4.3.5 elaborates further on this.
5. Checking the results of the application of the AHP with the expectations of the ones who completed the pairwise comparison (Russo & Camanho, 2015).
6. Decision documentation including the recording of all reasons supporting how and why the decision was made (Russo & Camanho, 2015).

Intensity of Importance	*Definition*	*Explanation*
1	Equal Importance	Two activities contribute equally to the objective
2	Weak or slight	
3	Moderate importance	Experience and judgement slightly favour one activity over another
4	Moderate plus	
5	Strong importance	Experience and judgement strongly favour one activity over another
6	Strong plus	
7	Very strong or demonstrated importance	An activity is favoured very strongly over another; its dominance demonstrated in practice
8	Very, very strong	
9	Extreme importance	The evidence favouring one activity over another is of the highest possible order of affirmation
Reciprocals of above	If activity *i* has one of the above non-zero numbers assigned to it when compared with activity *j*, then *j* has the reciprocal value when compared with *i*	A reasonable assumption
1.1–1.9	If the activities are very close	May be difficult to assign the best value but when compared with other contrasting activities the size of the small numbers would not be too noticeable, yet they can still indicate the relative importance of the activities.

Figure 10: The fundamental scale of absolute numbers (Source: Saaty, 2008)

Within this study the AHP-method was adopted as means to develop a decision-making model. While the problem definition and demarcation of the assumption underlying this research was done in the introduction (**section 1.1** & **1.4**), the determination of relevant knowledge needed was done during the orientation phase (including literature review and unstructured interviews). The semi-structured interviews (**section 4.2.2**) were used to collect relevant data as input for the construction of the matrixes. In order to increase validity of the questionnaire results, these were briefly discussed in the focus group. The focus group transcript covers the decision documentation (step 6).

4.3 Data analysis

4.3.1 Semi-structured Interviews

With authorisation by the interview respondents, obtained at the beginning of each interview together with an explanation of the confidentiality, procedure of granting the possibility of giving feedback on the transcript and aggregated report of the results, all interviews have been recorded using either a recording function on the researcher's mobile phone or the integrated recording function within Microsoft Teams. Recording has been done for two reasons. First, it enables the researcher to focus on the interview itself and therefore on the interview respondent including non-verbal communication. Secondly, after transcribing the recording it enables the research to analyse the interview using software. Within this study it was made use of ATLAS.ti (version 23.1.1), which is a coding programme specifically designed to analyse [*unstructured*] qualitative data. The tool supported the research in locating, coding and annotating relevant text passages in the interview transcripts (Konopásek, 2007). Coding mechanisms enable the researcher to compare interviews in a structured way, in order to reveal connections between statements made by the different interview respondents, organise these in a well-structured way (Cobe, 2010) and connect them to the pre-defined research objectives and corresponding questions (Konopásek, 2007).

The coding scheme that guided the deducting way of coding, whereby a pre-defined list of codes is composed before coding is done which helps focusing on issues that are important (Miles et al., 2013), can be found in appendix 4.6. The interview questions were drawn up based on literature study, unstructured 'interviews' with various experts/researchers the within energy transition domain prior to the initial primary data collection. Due to the different backgrounds of the interview respondents and the advancing level detail discovered by the researcher the interview questions were slightly adjusted during the process. Appendix 4.7 contains an illustration of the analysis/coding process within ATLAS.ti.

4.3.2 Questionnaire

The results from the questionnaire contain next to information about the respondent and willingness to participate in a follow-up focus group, results from individual the pairwise comparison of all the relevant criteria informing the multi-criteria analysis.

While the personal information about the respondent has been organized in an excel-sheet with no additional analysis required, the analysis of the results from the pairwise comparison is described in **section 4.4.5**.

4.3.4 Focus group

The procedure for analysing the results from the focus group was comparable to one of the individual interviews (section 4.4.2). A recording, authorized by the participations, was used to make a transcription of the focus group discussion. This was transferred to ATLAS.ti for coding and annotating relevant text passages. A pre-defined list of codes (see appendix 4.8) was used for deductive coding.

Nevertheless, important distinctions have to be made when analysing focus group results compared to individual interview results. Through the discussion inherent to a focus group interaction data [*between the respondents*] arises next to individual data in form of statements (Duggleby, 2005). Therefore, besides identifying evidence relating to certain topic based on deductive coding of the transcript, the level of consensus between the respondents was assed using a matrix (see appendix 4.9). In this matrix the researcher documented the number of focus group participants who agreed or disagreed with a certain statement. This allowed the researcher to supplement the qualitative data with quantitative data (Onwuegbuzie & Teddlie, 2003).

4.3.5 Multi-criteria analysis - AHP approach

While the process of obtaining relevant criteria informing the decision hierarchy and input for the pairwise comparison is described in the sections 4.4.2 till 4.4.4, the computation of the weights per criteria is described here.

Table 4.3: Example of completed matrix by respondent

	Uitvoerbaarheid overstap	Afstand tot backbone	Aantal monumenten	Sociale acceptatie	Percentage corp. Bezit	CO2-besparing	Verduurzamingsopgave
Uitvoerbaarheid overstap	1	1/5	4	1/3	6	6	5
Afstand tot backbone	5	1	3	1/4	6	4	4
Aantal monumenten	1/4	1/3	1	1/6	2	2	1/2
Sociale acceptatie	3	4	6	1	4	5	4
Percentage corp. Bezit	1/6	1/6	1/2	1/4	1	2	1/3
CO2-besparing	1/6	1/4	1/2	1/5	1/2	1	1/4
Verduurzamingsopgave	1/5	1/4	2	1/4	3	4	1
SUM	9,78	6,2	17	2,53	22,5	24	15,08

As described in section 4.3.5 a matrix of pairwise comparisons is used to identify how much more important or dominant one criterium is compared to another. Table 4.3 shows a completed matrix by one of the survey respondents as example. As seen in this table, there is a consistent value of 1 along the diagonal which is logical since every criterium is compared to itself here. With all pairwise comparisons completed by the survey respondents, the results are used to first check for consistency in judgments [*between the different respondents*] and secondly to compute the importance weights informing on how much each criterium factors into the decision. Both the consistency ratio (CR) and computation of the importance weights is done based on the Eigen Value method from Saaty (2008). In order to compute both, a normalized version of the pairwise comparison matrix has been created (table 4.4). This table includes the relative weight of each criterium, which is derived at by first calculating the geometric mean (V) for each row using formula (1) and then normalising the mean to ensure the sum of all weights (W) equalling 1 or 100% using formula (2).

$$V1 = \sqrt[n]{x11 * x12 * (\dots) * x1n} \qquad (1)$$

$$W1 = \frac{\mathrm{V1}}{\mathrm{V1+V2+\cdots+Vn}} \qquad (2)$$

Table 4.4: Normalized version of matrix displaced in table 4.3.

	Uitvoerbaarheid overstap	Afstand tot backbone	Aantal monumenten	Sociale acceptatie	Percentage corp. Bezit	CO2-besparing	Verduurzamingsopgave	**Relative weight**
Uitvoerbaarheid overstap	0,1022	0,0323	0,2353	0,1316	0,2667	0,2500	0,3315	0,17739
Afstand tot backbone	0,5111	0,1613	0,1765	0,1316	0,2667	0,1667	0,2652	0,246485
Aantal monumenten	0,0256	0,0538	0,0588	0,0658	0,0889	0,0833	0,0331	0,061154
Sociale acceptatie	0,3066	0,6452	0,3529	0,3947	0,1778	0,2083	0,2652	0,351527
Percentage corp. Bezit	0,0170	0,0269	0,0294	0,0987	0,0444	0,0833	0,0221	0,04288
CO2-besparing	0,0170	0,0403	0,0294	0,0789	0,0222	0,0417	0,0166	0,034651
Verduurzamingsopgave	0,0204	0,0403	0,1176	0,0987	0,1333	0,1667	0,0663	0,085913

Consistency ratio

In order to check for consistency among all respondents the CR for both respondents and matrices has to be checked. While some scholars (Saaty, 2008; Taherdoorst, 2017) suggest a threshold set at 0.10 for internal consistency, Pelaz and college's highlight the fact that '*for matrices of order greater than 6, the percentage of matrices accepted as consistent is almost null*' (2018, p. 25602). The CR is calculated using the consistency index (CI) and the random index (RI) according to the following formula (3)

$$CR = CI / RI(n) \qquad (3)$$

Here the consistency index in turn is measured through the following formula (4)

$$CI = \frac{\lambda \max - n}{n-1} \qquad (4)$$

While the random index is related to the dimension of the matrix and pre-calculated indexes (see figure 11) can be used here (Taherdoorst, 2007), λmax the so called principal eigen value (Saaty, 2008) is obtained from the summation of products between each element of the eigen value and the sum of columns of the reciprocal matrix (Teknomo, 2007).

Dimension	*RI*
1	0
2	0
3	0.5799
4	0.8921
5	1.1159
6	1.2358
7	1.3322
8	1.3952
9	1.4537
10	1.4882

Figure 11: Value of Random Consistenc Index (Golden & Wang, 1990)

Using the example from above (table 4.4) one derives at the following values:

λmax = 7.989
CI = 0.164
RI = 1.33
CR = 0.123

With a CR of 12,3% the ratio is above the 10% threshold. Furthermore, from table 4.4 it gets visible that criterium 'social acceptance' factors the most (with 35%) and criterion 'CO2-reduction' factors the least (with 3%) into the neighbourhood prioritization.

4.4 Ethics and positionality

Within academic research, especially while collecting primary data, it is important to consider a variety of ethical matters to enhance research credibility (Clifford et al., 2010). In order to ensure all relevant ethical issues were adhered to, the researcher followed the guidelines of the Research Ethics Committee of the Faculty of Spatial Science (Research Ethics Committee of the FSS, 2023).

In this study several ethical considerations have been made. First, to avoid privacy issues with regard to the personal information of the interview and focus group participants, all names and company names have been anonymized in the public friendly version of this thesis. Secondly, respondents have been asked about their consent to record the interview and focus group. Thirdly, the questionnaire started with a statement explaining the aim of the research, that participating in the study is anonymous and voluntary, and that participation can be ended at any moment. Questionnaire participation was only able when respondents agreed to these terms, otherwise they were directed directly to the end of the questionnaire.

Next to the ethical considerations, it is necessary for the researcher to reflect on his positionality (Wilson et al., 2022) in order to enable the reader to assess the effect of the identity of the researcher on the research process and results (Savin-Baden & Major, 2013).

The positionality is identified by locating the researcher's position in relationship to the topic under investigation, the participants in the study, and the research design (Holmes, 2020). According to Berger (2015) the background of the researcher [*consisting among others of experience in prior research, knowledge about the topic and attitude towards the research objectives*] can have an influence on the formulation of questions, interpretation of results and deducting conclusions. Since knowledge is not an objective given but rather socially constructed (Healy, 1997; Rydin, 2007), the aim of this study was to co-construct [*together with several experts*] knowledge about the potential position of hydrogen within the heat transition of the built environment and about the components of a suitable decision-making model.

Therefore, it should be noted that the researcher is aware about his positive attitude towards the application of hydrogen as energy carrier in the built environment and his keen interest in the heat transition which might have had an influence on how [*and which*] questions were posed, and answers were interpreted.

5. Results and discussion

In this chapter, the results of analysed data from the semi-structured interviews, questionnaire and focus group are presented. The chapter is divided into two main parts focussing on first the general investigation and secondly the development of the decision-making model, based on the schematic research approach discussed in **section 1.5** (see figure 1). Furthermore, each section is devoted to one of the five sub-questions outlined in **section 1.2**. In these sections, the collected data will be presented ana analysis with regard to the overall topic of this research, namely the application of hydrogen as energy carrier in the built environment.

Referring to the results
With this chapter extensively referring to the results of semi-structured interviews, survey and focus group, it is important to understand how these data sources are referred to in the analysis.

- Semi-structured interviews: In the next sections, the transcripts of the different interviews will be referred to. In case of integration of statements in the text, these will be referred to ending the sentence with (I#). When quotes are used in the following section, they will be highlighted using the colour 'gold, accent 4' and ending the quote with (I#). The number indicates the interview-respondent (see table X in section X).
- Survey: With only containing relevant results for the outcome of this study about the individual weighing of the different criteria for the decision-making model, a separate sub-section is devoted to these results (**section 5.2.2**).
- Focus group: In the next sections, the transcripts of the focus group will be referred to. In case of integration of statements in the text, these will be referred to ending the sentence with (F#). When quotes are used in the following section, they will be highlighted using the colour 'orange, accent 2' and ending the quote with (F#). The number indicates the interview-respondent (see table X in section X).

5.1 General investigation

5.1.1 The potential position of hydrogen as energy carrier in the built environment

This section presents the results linked to the answer of sub-question 1: "*What is the potential position of hydrogen as energy carrier in the heat transition of the built environment?*". While in line with the focus of this research, sub-question 1 elaborates on hydrogen as energy carrier in heat transition of the built environment, its potential position can't be established without also considering its position in the wider context of the energy transition, according to the interview respondents. Therefore, on both is elaborated on.

Among the interview respondents there is a broad consensus that hydrogen as energy carrier will have an important role in the energy transition as well as in the heat transition within the built environment, comprehensively described by respondent 7 *'I think hydrogen will play a crucial role in the transition. And why? Because considering the fluctuating sustainable energy* *sources, wind and sun, storage and balance between production and demand is becoming increasingly important.'* (I7). The ability of hydrogen to buffer the surplus in renewable electricity contributing to the solution of the intermittency problem (described in **section 2.2**) is also acknowledged by respondent 8: *'Electricity can be stored in batteries yes, (…) but those things run empty if you don't do anything with it, then you have lost it. And gas can easily be stored and transported, therefore I foresee that hydrogen is simply a good contender in the energy transition.'* (I8). This goes in line with what respondents 5 says about the promising application of hydrogen in relation to its potential position in the energy transition, as well as heat transition: *'The combination of electricity and hydrogen with heat surrounding both of them is the combination of energies that you want in a sustainable society.'* (I5), followed by: 'The role of hydrogen is, of course mainly where electricity falls short. Then you are talking about large-scale storage, about large-scale long-distance transport. Then you are talking about a certain part of the existing building stock.' (I5). The [*potential*] shortcomings of the electricity grid are addressed by respondent 3: *'(…) not everything [amount of energy produced and demanded] can simply go through the electricity grid. Therefore, it is essential to apply hydrogen as energy carrier in the energy and heat transition.'* (I3). While there is unanimity among the respondents that electricity as primary energy source should be used first to avoid conversion losses as expressed by respondent 5 'since almost all renewable sources initially produce electricity, say wind and sun, it makes sense that you always have electricity as your first choice' (I5), the advantages of using hydrogen as gaseous energy carrier are acknowledged, especially in relation to transport capacity of the existing gas infrastructure: *'gradually more awareness has come for the enormous amount of energy that can through the gas network.'* (I5).

Whereas there is a broad consensus among the respondents that hydrogen as energy carrier will play an important role in the [*heat*] transition of the built environment, there seems to be less consensus about the issues of time (both when and how long) and spatial location (where) regarding the built environment. These issues are nicely described by respondent 4: *'The heat transition is a jigsaw puzzle with hydrogen being one of the many pieces. There are more locations where you shouldn't want anything with hydrogen than there are locations where you want something with it. But still, there are locations where it is societal interesting to take a closer look. Furthermore, this puzzle consists of 1000 pieces and most people want to put them together in one go, but this is not possible.'* (I4). That the heat transition and its corresponding implementation takes time is also acknowledged by other respondents (I5; I6; I9, I10), with respondent 9 arguing: *'It is now the case that probably 90% of the households in the Netherlands still heat on gas. Then you can ask yourself whether we can make the transition all the way to [for example] all-electric? I don't think so. And I certainly don't think so all at once.'* (I9). Next to the issue of when the potential transition to hydrogen as sustainable energy carrier in the built environment is made, the issue of temporality emerged as a topic in the interviews. While for some hydrogen could function as a temporal solution (I6; I9; I10) coined for example as *'transition resource to buy time towards 2050'* (I9) or used in hybrid-applications where '*hydrogen is used in combination with electricity for a heating pump, until the moment that the resident decides to switch to full electrification.'* (I6), others (I1; I2; I4; I7) foresee a permanent role for application of hydrogen as energy carrier in the built environment due to the possibility of using existing infrastructure for the transport (I1), explained by respondent 1 as: '*hydrogen is also a very nice medium to be transport through* *existing gas infrastructure, therefore reusing the local gas grid instead of premature amortisation.'* (I1).

Regarding the spatial location where hydrogen as energy carrier can play a role in the heat transition of the built environment, six of the interview respondents see the technological potential of being implemented fairly simple due to few adaptations needed in the building (I1; I2; I3; I4; I7; I8), while also acknowledging the challenges regarding the limited supply (I1; I3; I6; I7; I10) expressed strikingly by respondent 10: *'(…), there is of course a ranking [in who should get hydrogen first], which I didn't come up with but I still accept. (…). For the built environment it won't be an option for some time, due to limited availability.'* (I10). (The other four respondents don't mention it.) While respondent 3 takes a comparable stand arguing that 'there is still a lot of uncertainty in this, and that has to do with the availability, but also with the cost' (I3), he also highlights that *'despite we don't know how big it [application of hydrogen as energy carrier] will be, we do expect it to be used in the built environment at certain locations.'* (I3). Another financial aspect stressed by several respondents is the relative cost of applying hydrogen as energy carrier, including the cost of the gas itself, repurposing cost of infrastructure and in-house adjustments, in relation to other sustainable alternatives (I2; I4; I6; I7; I9; I10), comprehensively described by respondent 4: *'So I advocate for hydrogen in locations where it is [economically] wise, I advocate heat networks in locations where it is wise, and I advocate for all-electric solutions where it is wise. Like this we keep it affordable, I hope. It's getting expensive anyway.'* (I4).

Several suitable locations for the potential application of hydrogen as energy carrier in the built environment are recognized by the interview respondents, with monumental buildings, buildings in remote areas and areas with a lack of space in the underground being the most prominent ones. The latter one is described by respondent 7 using the example of the city of Delft *'I always jokingly say the inner city of Delft. Old monumental buildings, a canal house, a street of max three meters wide. And these houses already have a high energy demand. Putting additional energy infrastructure [such as a heat network] in the street which is already completely full of other infrastructure [existing gas infrastructure, cables, waterpipes] will be a gigantic challenge. That are locations where a sustainable molecule, a gaseous energy carrier as hydrogen, will probably stay for some time'* (I7), while respondent 6 described the former two as: *'that might the 10% of the most complex neighbourhoods with old buildings that stand wide apart from each other'*. (I6). On the other side, there is a broad consensus where hydrogen as energy carrier probably won't play a role in the heat transition of the built environment, such as in new residential developing areas and existing buildings constructed starting from 2000. Respondents 2 put is as: *'Generally, I think that new homes are all-electric anyway and existing homes from the year 2000 onwards which are still reasonable to insulate, they can also be made all-electric. Anything older than that has more potential to transition to hydrogen.'* (I2).

Finally, while the exact spatial allocation of hydrogen as energy carrier in the built environment is prone to several uncertainties, a spatial fragmentation is expected by the interview respondents: *'So you would start to see a lot more fragmentation and I think right now we don't have the luxury of ruling out any options.'* (I7).

5.1.2 Technical fitness of existing local gas transport infrastructure for hydrogen transport

This section presents the results linked to the answer of sub-question 2: "*To what extent is the existing gas transport infrastructure on the local scale from a technical perspective suitable for providing the required amount of energy in the built environment when using hydrogen as energy carrier for heating purposes?*". While this section in line with the adopted research scope (described in **section 1.4**) predominantly elaborates on the technical fitness of the existing local gas grid [*from the regional entry point up to the gas meter*] for hydrogen transport, the in-house installation is briefly touched upon to provide a more coherent picture. The findings on technical fitness of the different components of the local gas infrastructure system will be presented following the order of questions posed in the semi-structured interviews (see **appendix 4.2** for the interview guides).

When looking at the **materials** applied [*in the local gas distribution grid*] there is consensus between the respondents that all materials are suitable for the transport of hydrogen: *'all materials that I just mentioned such as PE's, PVS or steal, those all suitable. So, all of them can be used one-on-one for hydrogen transport.'* (I2). Respondent 2 continues with elaborating on the smallest components of the local gas infrastructure: '*Within the low-pressure grid we sometimes use components called sleeves* (Dutch: moffen)*, into which the tube is slid and sealed with for example two rubber rings. Well, even the rubbers in those sleeves, (…), they are also suitable for hydrogen*.' (I2). Similar responses on the question of technical suitability of the materials for hydrogen transport have been recorded: *'All component materials are suitable.'* (I7), or *'Yes, everything is suitable for hydrogen transport. As it seems now also the various materials used in the stations.'* (I3).
However, a small footnote is made by all interview respondents on this matter, comprehensively highlighted by respondent 5: '*there a few minor exceptions. A few old materials that we don't want, we want to get rid of (…). Materials like gray cast iron or asbestos cement are not suitable, but also not desired in the grid anymore.'* (I5). This goes in line with what respondent 3 says: '*We have established [through field research] that all materials are suitable, expect for asbestos cement and gray cast iron.'* (I3), while a quote of respondent 4 complements this: *'(…) and then a new pipe made from PE or PVC will be placed there. It says even on these pipes "suitable for hydrogen" nowadays'*. (I4).

The local gas distribution network and its corresponding infrastructure components have as starting point the regional entry point, where a so-called gas transfer station (Dutch: gas overdrachtsstation, GOS) is located. While the **transfer station** is still within the area of the responsibility of Gasunie everything after that up to the gas-fired boiler (including the gas meter) is the responsibility of the regional network provider (I2; I5; I7). Somewhere between the regional entry point and the gas meter of an individual building a district station is located: *'(…) and then it [the gaseous energy carrier] goes to a district station. That is a neighbourhood distribution box, and here the pressure is reduced to 100 millibar again. (…) Sometimes there are 300 homes behind it, sometimes there are a thousand five hundred homes behind it, depending on the demand.'* (I3). When looking at the technical fitness of transporting hydrogen as energy carrier or operating with it the same positive conclusion as with the material discussed above are drawn by the interview respondents: *'the functionality of such station works one-to-one as with natural gas. All the safeties fell at the right moment. The control behaviour checking the amount of gas needed dependent on the amount works well.*

So, technically it can all be reused.' (I2) or *'Such a pressure regulator works autonomously. That's just a setting with springs and counter forces. (…). That dynamic effect is just a bit different with hydrogen. That is something that needs to be reset, but the components themselves are gas-tight and can therefore be reused.'* (I5).
When specifically asked about the issue of [*potentially*] increased risk of oscillation due to the increased velocity of hydrogen (see for the theoretical discussion **section 3.3.1**) the interview respondents showed divided opinions. While respondent 2 foresees no problems: '*at those speeds no strange things have happened so far. So according to current insights that seems to go fine. (…). In fact, at stations noise measurements have shown that it even decreased.'* (I2), respondent 7 expresses slight concerns about the increased velocity: *'this means that a phenomenon such as vibration increases with speed, so vibration effects can play a part especially in places where the passage [for hydrogen] is small. You can think of stations that reduce the pressure.'* (I7). Overall, the interview respondents don't foresee any challenges with the current **stations** in the local gas distribution grid (I2; I3; I4; I5; I7).

When investigating the **in-house installation**, both the gas meter and the gas-boiler are considered as the components that have to undergo a wide-ranging conversion, better said a replacement (I2; I3; I4; I5; I6; I7), comprehensively expressed by interview respondent 2 as: *'where the biggest changes have to come and you indicated it yourself is within the house, especially the boiler because the burner is not suitable.'* (I2) and the respondent continues: *'Then you go even further back to the indoor installation. Then you arrive at the spot where the gas from us enters the households. Here you have the meter setup. (…). The meter of natural gas is not suitable for hydrogen, so it has to be replaced.'* (I2). With regard to the gas meter, the exact meaning of 'technical fitness' has been put to test leading to dissent between the interview respondents. While in line with respondent 2 claiming that the meter needs replacement respondent 3 declares that *'(…) the meter needs to be replaced. A meter at your home, for example, can sometimes six cubic meters per hour, and with hydrogen [as energy carrier] that should actually be eighteen cubic meters. And that is not possible because of the meter.'* (I3), respondents 4 and 7 have a different conception of the term 'technical fitness' therefore arguing that the current meters can transport [and process the amount of] hydrogen without any problems (I4; I7). This is well illustrated by respondent 4: *'Is the current gas meter not running? Well, it runs fine and goes just three times as fast. The biggest problem is that it is not countable* (Dutch: comptabel)*. And what does that mean? That means it wouldn't be very accurate according to the energy company.'* (I4).
A broad consensus among the interview respondents considering the need for replacement of the gas-fired boiler. As already touched upon with the quote of respondent 2 indicating that the burner, the *'heart of the boiler'* (I4), is not suitable, respondent 5 explains: *'the boiler itself is [in a hydrogen-based scenario] a different boiler, because a natural gas boiler cannot simply handle 100% hydrogen. (…). So, the boiler needs to be replaced.'* (I5).

While the above presented findings elaborated on the technical fitness [*implying the suitability of material and components in the local gas distribution grid*] for the transport of 100% hydrogen as energy carrier [*being a sustainable alternative for natural gas*] in the existing infrastructure, the last part of this section focusses briefly on [*technical*] **capacity to deliver** sufficient energy in the form of hydrogen [*in kWh/m3*] for heating purposes in the built environment. Here broad consensus among the interview respondents exists again (I2; I3; I4; I5; I7): '*It is still possible to get sufficient energy to the boiler through the existing grid.'*

(I4). Respondent 4 elaborates on this by explaining: *'The gas network has been enormously oversized in recent years. In addition, the demand for heat has decreased considerably in recent years.'* (I4). This goes in line with the argument of respondent 5 claiming that *'Regarding the dimensioning [of the local grid] it won't be a problem.'* (I5). When considering the lower calorific value of hydrogen (**see section 3.3**) and therefore the need for a larger amount of gas [*in m3*], the interview respondents foresee no problem for sufficient energy delivery for heating purposes because of the properties of hydrogen on molecule level: *'For the same amount of energy, you need three times as much hydrogen. (…), in the pressure formula, the density of hydrogen and the calorific value [the quantity of energy] annual each other. So, the pressure drop in the pipeline at three times as much hydrogen is equal to [the pressure of] natural gas.'* (I2). Respondent 4 explains it similarly as: *'The calorific value is a factor three lower compared to natural gas, but the speed is [for the same pressure] three times higher, so the effect is about the same.'* (I4) and concludes: *'We haven't found any limitations there yet.'* (I4).

Challenges in the transition from natural gas to hydrogen as energy carrier

Despite there prevails a broad consensus among the interview respondents about the technical fitness of the existing local gas infrastructure for the transport of hydrogen, a couple of challenges for the actual transition from natural gas to hydrogen as energy carrier are highlighted, especially when considering a large-scale transition outside a [*highly monitored*] pilot project environment.

While the 'only' technical challenge being the risk of contamination due to the presence of sand residuals in the gas pipes distribution described by respondent 7 as *'sand grindings can be present in the gas network due to working activities. (…) we have filters to filter out that small amount, but we are curious what will happen in a situation where three times as many molecules pass through it [the pipes] at high speed. Will the sand become lose and potential clog the filters?'* (I7), the most prominent challenge is for planning reasons (I2; I3; I4; I5; I7). Therefore, respondent 2 describes it as *'If you are looking for what are technical challenges? Then that is actually the practical transition, and it is not even very technical. It is mainly a planning issue.'* (I2). As outlined above, the current in-house installations are not compatible with hydrogen as energy carrier (gas-fired boiler) or from a legal standpoint not calibrated for hydrogen (gas meter). Albeit the [*theoretical*] transport of hydrogen through the existing gas infrastructure system even up to the gas boiler might be possible, heating using hydrogen as energy carrier wouldn't be possible: *'So theoretically everything should work [considering the responsibility area of the network provider]. (…). I think what the greatest impact for us as network provider has that it is a different gas.'* (I2).

The planning related challenge is metaphorically coined as *'military operation'* by respondent 7: *'And why do call it like this? You are renovating while the store open is. You have a natural gas network that is robust because it is meshed everywhere and that has security of supply with the arteries and connections between stations. And what you are actually going to do you are going to cut up the existing network configuration.'* (I7). This issue is also recognized by other interview respondents: *'So the challenge or complexity, (…), is the conversion to hydrogen if you look at a certain service area which is very meshed.'* (I4) or *'So we have to plan very well and take a very good look at each building: where can we smartly make those cuts*

to ensure that not too many homes come detached from the current [natural gas] grid, and whether you can already transfer certain parts.' (I3).
In order to convert an individual home from heating on natural gas to heating on hydrogen as energy carrier a couple of preparations have to be made. Inherent to the planning of/for these preparations is a high degree of complexity (I2; I4; I7) because they have to take place during a limited timeframe (a part of the day) or simultaneously, depending on the number of buildings that are converted at once (I1; I4; I7; I8). This is described by respondent 5 as: *'(…) such a conversion is quite a lot of work, because you have to work synchronously at the outside and inside. Outside you have to close things off, clean [the pipes], the natural gas-fired boiler has to be removed from the wall, the gas meter has to be replaced, a hydrogen-fired boiler has to be mounted on the wall. Outside, everything has to be connected to the hydrogen and then you can activate the systema again.'* (I5). The process of conversion is described in a similar way by respondent 7: *'The natural gas feed goes off in the morning. The installer enters to replace the heating boiler. (…). Then we can clean the pipes in the main grid outside, test it and fill it with hydrogen. (…) At the same time the installer says "I am done, the new boiler is mounted. Then we flush the indoor installation because there is still air in it (…). A certain point you say that it [the indoor installation up to the boiler] is now 100% filled [with hydrogen] and only then you can turn on the boiler. And so that are quite a few actions that you have to in a day.'* (I7), while already highlighting the [*potential*] issue of residents not being home (I7).
The complex operation of conversion (I2; I4; I7) fits [*again*] in the frame of the prior described jigsaw puzzle: *'I'm talking about that puzzle again. You start with a piece [of the area you want to convert]. If you say I must have the same security of supply: (…) the whole Netherlands [or a whole neighbourhood] on hydrogen at the same time, that's not possible.'* (I4). This goes in line with how respondent 5 frames it: *'If you want to this [the conversion from natural gas to hydrogen] with thousands of homes or to convert a neighbourhood in a [for example] week (…), while puzzling about this, I noticed that it is quite complex that it involves a lot [simultaneously activities], there is a lot of preparation and that many people are need to carry it out. All this makes it quite a planning risk.'* (I5).

Albeit the above-described planning related issue is identified as the most challenging one [*considering the current pilot project environments*], two other challenges are highlighted that might become of increasing importance when considering a [large-scale] rollout of the application of hydrogen as energy carrier in the built environment. These are framed as more social aspects of the transition towards hydrogen as energy carrier (I3; I4; I7). While one is a matter of internal [*organisational*] *'culture shift'* (I2) because of changes in the manner of working: *'I think the biggest difference for the mechanics is that they have to work with nitrogen as inert intermediate gas.'* (I5), the other is of social acceptance [*for hydrogen as energy carrier*] from residents (I1; I3; I4; I6; I9; I10) with *'the most important [aspect] being that it is not possible to cut someone off from natural gas if they don't want to in the Netherlands.'* (4).

5.2 Development of the decision-making model

5.2.1 Relevant criteria for the multi-criteria decision-making model

This section presents results linked to the answer to sub-question 4: "*What are relevant criteria on the local level potentially informing a spatial multi-criteria analysis for prioritizing suitable neighbourhoods for the application of hydrogen as energy carrier?*". In line with the research scope (**section 1.4**) only criteria on the local level (municipality) are considered and consequently elaborated on here. While the identified criteria will be presented one by one, following from the order of questions posed in the semi-structured interviews (see **appendix 4.2** for the interview guides), this section starts with presenting two 'exclusion' criteria. When applicable for a certain neighbourhood, these criteria lead to the exclusion of the neighbourhood [*in further analysis*].

Complete consensus among the interview respondents prevailed regarding the issue of presence of gas infrastructure: *'a gas grid has to be in place, otherwise we wouldn't be able to use it for hydrogen transport'* (I1). Respondent 4 expressed this similarly by: *'what helps is the presence of [current] infrastructure. This of course a very important criteria to transport hydrogen.'* (I4). In order to transport hydrogen as energy carrier to an area or a single building, gas transport infrastructure in form of distribution pipes has to be present, otherwise the supply of the built environment with hydrogen as energy carrier would require the construction of new [*gas*] infrastructure therefore [*completely*] missing the point of repurposing infrastructure: *'if you first need to install pipes.. this would go against our desire to make you use of the existing one.'* (I3). While associated with the issue of availability of gas distribution infrastructure respondent 6 adds: *'In areas where no gas grid is present, the use of hydrogen as energy carrier isn't a logic choice anyway because most of the time we are looking at areas constructed after [July] 2018 where there is no gas connection allowed anymore according to the gas law and where other sustainable alternatives are a better solution.'* (6) which connects well to the second exclusion criteria. In line with the 'heat transition map for the built environment' every municipality has to have since 2021, each neighbourhood has the most 'suitable' sustainable alternative assigned to it, with all-electric, a heating network or a hybrid solution as the three [*most common*] alternatives. The interview respondents argue that hydrogen as energy carrier should [*only*] be used in neighbourhoods where no other alternative is an option (I2; I3; I4; I5; I7; I8), comprehensively described by respondent 2 as: *'The most important step is first to look which neighbourhood might be a potential hydrogen neighbourhood. So, [a neighbourhood] where no other option is available. There is so much focus on this from the national level: first look at all-electric, secondly at heating networks and then the rest could be done using hydrogen [as energy carrier].'* (I2). This goes in line with how respondent 7 frames: *'(…) Where are other [sustainable] options suitable? And then you are going to colour that in starting at the locations where you don't have to doubt a certain location, because that's a very suitable solution for a heating network or all-electric. And the blanks.. you don't know exactly where those might be'.* (I7). Examples for locations where the application of hydrogen as energy carrier wouldn't be suitable are given by respondent 5 with regard to heating networks: *'(…) we also take into account alternative infrastructure. So, buildings close to each in the vicinity of a potential heat source, there you look into whether you can do something with heat networks.'* (I5) and by respondent

7 regarding all-electric: '*then you can think of for example net construction or relatively well-insulated building, which are very suitable for all-electric solutions.'* (I7). So, the decision regarding the allocation of [*scarce*] hydrogen is highly dependent on the other alternatives (I5) as explained by: *'(…). And at the moment we all still reason from a situation of scarcity [regarding hydrogen], then all-electric, heating networks or hybrid variants are better options for those purposes.'* (I7).

Based on the above-presented discussion hypothesis H2a and H2b (**see section 3.5**) can be supported. While the presence of existing infrastructure is a requirement for making use of the repurposing potential (H2b) this influences the development of the decision-making model. Similarly, taking the potential of hydrogen delivering high temperature heat (H2a) therefore its preferred allocation in areas where other alternatives are not suitable into account this influences the development of the decision-making model, especially acknowledging the [*current*] scarcity.

Distance to national hydrogen infrastructure

While further elaborating on the issue of scarcity, because of low production units and high prices for hydrogen (I3; I4; I9; 10), almost all interview respondents foresee the national hydrogen infrastructure [*so-called H2-backbone*], which is currently realised by the Dutch Gasunie (see **section 3.3**), as an important part in the hydrogen supply chain transporting hydrogen from centralized production locations through the country (I1; I2; I3; I4; I5; I7; I8). Therefore, the distance between a potential neighbourhood and the [*future*] backbone is identified as relevant criteria specifically regarding supply security of hydrogen: *'I think one of the most important criteria, is hydrogen availability in vicinity of a certain neighbourhood. (…). So, if a village or district is close to it [the hydrogen backbone] it will be of course a lot easier to provide hydrogen in the future. It will guarantee reliable supply.'* (I2). This goes in line with how other respondents describe it: *'[what important is] is the distance to the national pipelines of the Gasunie'* (I4), or *'We take as a starting point for our conversion plans the distance to the backbone. If you want to have affordable and reliable supply of hydrogen, then this has to come through the national backbone.'* (I6) or '*Assuming that the national backbone is in place, including regional connections. And if we then focus on the development of a hydrogen neighbourhood, so the very first start.. then I think it is crucial to be proximity of the backbone.'* (I7). According to the respondents choosing a neighbourhood farer away from the national hydrogen infrastructure would require a longer bypass [*in meters*] or the conversion of more existing gas infrastructure (I2; I4; I5; I6) jeopardizing the supply security of other neighbourhoods still heating with natural gas as energy carrier (I1; I2; I4; I7). Respondent 1 therefore argues: *'If you choose a neighbourhood far away from the backbone, this wouldn't be a handy location choice of course.'* (I1).

Monumental buildings

Often buildings with a monumental status, either from national, municipal or characterised as having an iconic front, are difficult to insulate because of a variety of restrictions (I10): *'(…) is it difficult to insulate or does it make the character [of the building] disappear? Monuments are perfect example for this. You can't put a cosy over that. So, if the historical value of the building is so high, you can't thinker with that too much.'* (I10). The presence of monumental buildings in decent amounts is brought forward as relevant criterion (I2; I3; I4; I6; I7; I8), because (of) *'the combination of age and the difficulty to heat such a building with a different alternative'* (I1) and *'these are old buildings where you can't make much progress in terms of* *reducing the heating demand'* (I6). Respondent 4 comprehensively describes the issue of monumental buildings as: *'Monumental buildings, buildings that are so poorly insulated that it would be smarter from an economic point of view to destroy them and build new ones. But we [as society] often don't want that. You have a beautiful old village [such as Stad aan 't Haringvliet] with beautiful old mills, a church and other monumental buildings. Yes, these we have to heat as well.'* (I4).

Percentage of housing stock owned by housing corporations
The conversion of a neighbourhood from natural gas to a sustainable alternative is a complex, time-consuming, and labour-intensive operation. Often the municipality, the housing corporations active in a certain a neighbourhood together with other stakeholders devote several years to such a conversion. Recent reports about the experiences of so-called 'natural gas free experimental neighbourhoods' (Dutch: Proefwijken aardgasvrij) illustrate that the complexity of handling with a variety of ownership constructions. Acknowledging these complexities there is broad consensus among the interview respondents that the presence of housing corporations' ownership is a relevant criterion (I3; I4; I6; I8, I9; I10), since especially high percentages of this would make the conversion to hydrogen more easily: *'more cooperative ownership helps, because only 70% of their renters have to agree to far-reaching renovations'* (I6). This goes in line with respondent 9 expressing: *'social rent means housing corporation ownership. There is a system behind this which would make the conversion [to hydrogen] easier because you only 70% consent'* (I9). Additionally, respondent 10 highlights the fact that with [*high percentage of*] housing corporation ownership much housing stock can be covered through only a couple stakeholders: *'(…) With housing corporations you of course have one or couple parties you have to address.'* (10).

Social acceptance
With 'all' technical solutions available to manage turning away from fossil fuel-based heating in the built environment, the heat transition [*and the energy transition as wider context*] is framed as a social transition (I6; I9): *'I think the transition is not a technical task, but a societal one.'* (I9). While existing consumer behaviour [*based on natural gas heating*] can partly hinder a transition in a [*socio-technical*] energy system (see **section 3.1**), social acceptance of an energy carrier like hydrogen is acknowledged as relevant criterion for the decision-making model (I4; I5; I6; I8; I9, I10): *'It is true that social acceptance and support really add up. These are things that make the transition easier.'* (I6). For respondent 4 this is even the most important criterion: *'My motto is no innovation without acceptance. You can have an idea ever so good, but when it is not accepted you can forget it. So, you have to make sure that you have support first. No support? Don't even start.'* (I4).

Diffuse spatial built-up
While being related to the exclusion criterion 'other suitable sustainable alternative' discussed above, four of the respondents mention a diffuse spatial built-up as potential criterion which is characterized by low density of buildings with considerable distances between the different buildings (I2; I5; I6; I10): *'For example the more rural areas. There is no industry, only few high-rise buildings, many buildings far apart from each other. Areas where we don't foresee a heating network or electrification. So, here hydrogen could play an important role.'* (I2). This goes in line with respondent 10 arguing for: '*So, for example small villages like Ten Post in the outskirts of the municipality. There it is not possible to connect the*

buildings on heating network because of the distance between the buildings, and all-electric is also not an option due to the character of the building.' (I10). While most of the interview respondents didn't mention this as a potential criterion (I1; I4; I7; I8; I9), respondent 3 don't think that this is relevant to consider: *'Why shouldn't buildings in these areas go all-electric? In my opinion this hasn't anything to do with the density of the built-up area, (…).'* (I3).

Potential local production

In light of the current pilot projects of the network provider that all rely on the delivery of hydrogen via tube trailers and partly foresee a local production on-side in the future, some of the respondents (I2; I3; I4; I9) mention the availability of space for a local production unit in a neighbourhood as possible criterion: *'So, a possible location within the neighbourhood where hydrogen could be produced locally would be an option, because then you don't have to vacate part of the current gas grid to transport hydrogen into the neighbourhood.'* (I2). While the availability of space for either an input location or local production unit is acknowledged as convenient in the pilot projects expressed by respondent 3: *'This also gave more space to find a feed-in location. Imagine you have very dense city and you choose a residential area somewhere in the middle of the city, then you will make it yourself difficult.'* (I3), most of the [*other*] interview respondents either didn't even mention this as a possible criterion (I1; I6; I7; I8) or don't foresee local production in the future and therefore this issue not as a relevant criterion (I5; I10), as expressed by respondent 5: *'We don't believe in decentralized projects, because we think that the business case simply won't work. Think of [expensive] storage and everything.'* (I5).

Complexity of insulating on larger scale

While the complexity of insulating a specific building like in most cases a monumental building with a diversity of restrictions connected to it is discussed above, another issue is highlighted and therefore identified as relevant criterion by the interview respondents: *'(…) a neighbourhood as a whole that is very difficult to insulate.'* (I1). That is the complexity of insulating all [*residential*] buildings in a certain neighbourhood within a decent amount of time as preparation for a sustainable alternative of natural gas [*for heating purposes*] (I1; I2; I4; I5; I6; I8; I10). When preparing a neighbourhood for a certain sustainable alternative the first [*desired*] step is to reduce the heating demand through different types of insulation because this makes the connection to, for example, a heating network more effective. In a neighbourhood with a recurring housing typology built in a certain time period (e.g., post-war construction) a large-scale insulation operation is acknowledged to be simpler (see **section 2.3**). While a consensus on the general description of the criterion exists among the interview respondents, they highlight the importance of different components: '*In such neighbourhoods there are all kinds of building types from different periods with their own problems. (…) you have cities with different layers from different construction periods with their own energy problems.'* (I8) with goes in line with respondent 6 describing it as: *'there are buildings from pre-war, from the fifties, sixties or seventies, but there are also relative badly insulated houses from the around the turn of the century.. next to different typologies you have to deal with.'* (I6), or *'I'm thinking about complicated buildings where a lot has happened over the years. There is a shop downstairs, an apartment on the first floor, but also a lean-to in the garden and under the roof two individual studio's, plus also a mix of rent and ownership.'* (I6). To summaries, the interview respondents identified the year of construction and diversity in building periods (I1; I2; I4; I6; I7; I8; I10), the diversity in building typologies (I2; I5; I6; I7; I8;

I10) and the mix of rent/ownership (I4; I5; I6; I10) as components of this criterion, comprehensively expressed as: *'So, imagine you have neighbourhood where everything is the same. Post-war neighbourhood, everything built in the same period, mostly [social] rent. Here it will go way easier with making the neighbourhood sustainable, because of economies of scale.'* (I2).

Societal cost of sustainable alternative

While being inherently connected to the overall choice of which sustainable alternative for natural gas is applied in a certain neighbourhood, the issue of societal cost as a criterion is mentioned by four of the respondents (I3; I4; I7; I10), metaphorically described by respondent 4: *'Very important, I think, is that you do it from a societal perspective. If you only act from the perspective of the resident or only from the perspective of the network provider is one-sided. So, let's all put our wallets on the table. We'll make one big wallet out of it and then we'll see which [sustainable] option does cost us the least considering us one big cosy family?'* (I4). This goes in line with how respondent 10 see's is: *'Well, you have to look at it from a societal point of view, because it doesn't matter where the cost will be.. in the end we all pay them as the end user. (…), so you have to think: what is the most [cost] efficient solution?'* (I10).

Other respondents (I1; I5; I6; I9) also highlighted the fact that the societal cost for each sustainable alternative in every neighbourhood of the Netherlands has already been calculated by the Netherlands Environmental Assessment Agency (Dutch: Planbureau voor de Leefomgeving, PBL). Therefore, they don't deem it as relevant for the decision-making model.

CO_2-reduction

In line with the Dutch climate agreement the goal is to decarbonize the building sector by substituting natural gas with sustainable alternatives by 2050. An important intermediate goal is a CO_2-reduction of 60% by 2030. In order to realise these climate targets, especially for the target for 2030, it is deemed important by the interview respondents (I3; I4; I6; I9; I10) to elaborate on strategies regarding where CO_2-reductions can be realized in this timeframe. Taking the feasible CO_2-reductions by converting a neighbourhood to heating on hydrogen into account is acknowledged as relevant criterion by the respondents (I2; I3; I4; I6; I7; I8; I9; I10): *'How much it [a certain neighbourhood] contributes to the energy transition is I think an important aspect in your consideration.'* (I8).

Complexity of conversion from natural gas to hydrogen as energy carrier

The complexity inherent to the conversion of an area from heating with natural gas to hydrogen is acknowledged by all interview respondents as a relevant criterion. While this already elaborated on in section 5.1.2 (*challenges in the transition*) as an aspect with multiple challenges attached to it (planning-technical, cultural shift, consumer behaviour), the spatial component of this criterion is highlighted by the respondents (I1; I2; I3; I4; I5; I; I7, ;8) comprehensively described by respondent 2: *'To what extent it is doable to disconnect a certain area from the existing natural gas network. By that I mean, if you also close important supply pipes to the adjacent neighbourhoods through which the security of supply in adjacent neighbourhoods might be jeopardized. There is also an important economic aspect, so to what extent is it easy to connect areas [to a future hydrogen supply] without having to make a lot of investments.'* (I2).

Table 5.1: Overview of potential criteria

Criterion	Mentioned	Not mentioned	Not validated
Distance to national hydrogen infrastructure	I1, I2, I3, I4, I5, I7, I8	I6, I9, I10	/
Monumental buildings	I1, I2, I3, I4, I6, I7, I8, I10	I5, I9	/
Percentage of housing stock owned by housing corporations	I3, I4, I6, I8, I9, I10	I1, I2, I5, I7	/
Social acceptance	I4, I5, I6, I8, I9, I10	I1, I2, I3, I7	/
Diffuse spatial built-up	I2, I5, I6, I10	I1, I4, I7, I8, I9	I3
Potential local production	I2, I3, I4, I9	I1, I6, I7, I8	I5, I10
Complexity of insulating on larger scale	I1, I2, I4, I5, I6, I8, I10	I3, I7, I9	/
Societal cost of sustainable alternative	I3, I4, I7, I10	I1, I2, I5, I6, I8, I9	/
CO_2-reduction	I2, I3, I4, I6, I7, I8, I9, I10	I1, I5	/
Complexity of conversion	All	/	/

BOX 3: Interim conclusion on criteria selection
Based on the literature study, both the unstructured interviews and semi-structured interviews and multiple discussion with the supervisor and other experts, a final set of relevant criteria [*as input for the further development of the decision-making model*] is generated. Within the final selection several considerations have been contemplated. First, the selection had to represent the interest of the interviewed experts. Secondly, in terms of reliability only criteria that have been mentioned or validated by at least half of the experts have been deemed as relevant for processing.

This had led to the inclusion of the following criteria, each on/considering neighbourhood scale (Dutch: [*cbs*] buurtniveau): practicality of conversion from natural gas to hydrogen as energy carrier, distance to [*future*] national hydrogen infrastructure backbone of the Netherlands, percentage of monumental buildings, percentage of housing stock owned by housing corporation, social acceptance [of hydrogen as energy carrier for heating purposes], CO2-savings [*through replacement of natural gas with hydrogen as energy carrier*] and the complexity of making the urban fabric sustainable (diverse set of insulation measures).
While some of these criteria have a clearly defined spatial component, like the percentage of housing stock owned by housing corporations, for other criteria this is less clear such as for the distance between the national hydrogen infrastructure and the neighbourhood. Based on the results of the focus (**section 5.2.3**) the spatial demarcation has been further elaborated on.

5.2.2 Individual pairwise comparison of the criteria

This section presents [*a part of the*] results linked to the answer to sub-question 3: "*What are the relative weights for the different relevant criteria, explaining their importance in the overall decision-making?*". The online questionnaire containing the pairwise comparison, a method to assign weights to different factors in a decision-making process enabling the establishment of the relative importance of each criterium in the final decision, has been filled out by all ten interview respondents. Unfortunately, only four of the ten responses have produced reliable results. Reliable results are here understood as complete and correct filled in the question containing the comparison-matrix (see **appendix 4.4** for the questionnaire design). The issue of unsatisfactory questionnaire results is elaborated on in the reflection chapter of this study (see **section 7.2**). However, the fact that all ten potential respondents have filled in the questionnaire can be regarded as positive, because this represents a response rate of 100%.

Table 5.2: Combined weights based on all individual expert input (combined)

Criteria	**Weight of criteria**	**CR**
Complexity of conversion from natural gas to hydrogen (…)	12,4%	
Distance to national backbone	19,7%	
Percentage of monumental buildings	7,1%	
Social acceptance	40,7%	
Percentage of housing stock owned by housing corporation	4,1%	
Amount of CO2-reduction	7,8%	
Complexity of making the urban fabric sustainable	8,2%	4,3%

What can be observed from table 5.2 is that the consistency ratio between the individual answers of the four respondents is 4,3%. Therefore, the consistency lies within the 10% threshold proposed by among others Saaty (2008) or Taherdoorst (2017).
Next to that, the relative importance of the different criteria can be extracted from the table. With 40,7% social acceptance has the highest weight relative to the other identified decision criteria, indicating that the social acceptance [*for hydrogen as energy carrier in the built environment*] of residents in a given neighbourhood is the most important criteria when considering in which neighbourhood the application of hydrogen is suitable. According to the combined expert judgment, the percentage of housing stock owned by housing corporations is least influential (4,1%) in this decision.

5.2.3 Spatial demarcation and definition of the criteria

This section presents results linked to the answer to sub-question 4: "*"How can the identified criteria for the multi-criteria analysis be defined and spatially demarcated?".* In this section the information from the focus group is used to further define and spatial demarcate the final selection of the relevant criteria [*informing the decision-making model under development in this study*]. Therefore, this section builds upon **section 5.2.1** with small adaptions in the formulation of the 'name' of criteria to account for the final demarcation of each criterion. As indicated in box 1, the criterion of percentage of the housing stock owned by housing corporations was in itself spatial demarcated already. Therefore, no further elaboration is done here on this criterion.

Distance to (future) hydrogen infrastructure and sources

While during the interviews the importance of the distance between a certain neighbourhood and the [*future*] national hydrogen infrastructure realised by the Gasunie was mentioned as criterion expressed by interview respondent 4 as: *'[what important is] is the distance to the national pipelines of the Gasunie'* (I4), the focus group participants further elaborated on these by adding that also the distance to other infrastructure like the regional network, as well as other potential supply locations in the future are relevant parts of this criterion: 'I think it's not just about the national hydrogen infrastructure, but maybe a step further. (…). Perhaps you shouldn't call it national hydrogen infrastructure, but already existing or expected hydrogen infrastructure.' (G3) and *'What we're probably going to see is that a lot of cluster six industry (*Dutch: Regionale Cluster 6 industrieën, see for an explanation on these clusters: KNB et al., 2020*) is going to get connected to hydrogen as well. While that's not called the backbone, you already entering a regional infrastructure.'* (G3). This is acknowledged by respondent 2 expressed by: '*So, you have to see the hydrogen infrastructure somewhat broader than just the backbone, therefore include also the broader branch in your analysis.'* (G2). With regard to the spatial measurement, the focus group participants agree upon that measuring the linear distance (Dutch: hemelsbreed) between a (future) supply location or infrastructure component [*that transports hydrogen*] is sufficient (G1; G2; G3; G4), taking substantial spatial obstacles like a river or an estuary into account: *'You can consider all sorts of [spatial] complications, like a Westerschelde [being an estuary] or something like that. But basically: look at the linear distance.'* (G3).

However, adding to the complexity of the spatial demarcation respondent 2 highlights that the coverage area expressed in the volume of hydrogen that a certain neighbourhood might demand can play a role in this criterion: *'I guess it really depends on what's behind it. Things like volume play a role in being able to draw Gasunie's interest in connecting an area.'* (G2).

Monumental buildings

With the existence of different categories of monumental buildings in the Netherlands such as buildings with a national monumental status or buildings with a protected city view (Dutch: beschermd stadsgezicht), consensus among the focus group respondents pertains that no distinction has to be made between the different categories.

With regard to the quantification, expressing this simply in the number or percentage of buildings within a certain neighbourhood isn't the most preferred way: *'Concerning your other question if one should take the number or percentage of monumental buildings into account, I don't know if this is the right attitude.'* (G3). Respondent 3 continues by explaining: '*Even if there is only [one/a] Rijksmuseum in a neighbourhood surrounded by all newly constructed buildings [without gas consumption]. Is it then one building? Or is that for example 0.1%? But if it happens to be the one [building] that consumes most energy of everything in the area, then in becomes very decisive again.'* (G3). This goes in line with how respondent 4 expresses it: *'What you want to find out with this criterion is how dominant are the monumental buildings in the total gas consumption of a neighbourhood. Are you looking for example at a Rijksmuseum responsible for half of the total gas consumption or at an old farm where the consumption is neglectable?'* (G4). Accordingly, the relative amount of gas consumption of the monumental buildings factors into this criterion (G2; G3; G4).

However, respondent 1 highlights that the quantity either in numbers or percentage still plays a role in this criterion because it should aim at identifying neighbourhoods with a considerable quantity of monument buildings: *'But what you hope to get out of this [criterion] is that* *neighbourhoods come up with lots of monuments. Whether this is a canal belt or neighbourhood in ***********.'* (G1).

Social acceptance of hydrogen

Although the importance of social acceptance for hydrogen as energy carrier in the built environment is strikingly affirmed by all focus group respondents (G1; G2; G3; G4) well expressed by respondent 2 as *'I think that social acceptance is very important. You know my motto: Without acceptance, no innovation.'* (G2), no comprehensive statements on the spatial demarcation could be made. Next to that, using socio-demographic characteristics to build an indirect indicator have not been confirmed: *'I don't think that connecting social acceptance with certain demographic characteristics is the way to go.'* (G2).

Complexity of large-scale insulating on neighbourhood scale

Complete consensus among the respondents exists about that a neighbourhood where a large-scale insulating activity [*covering the whole neighbourhood with a one-size-fits-all approach*] is a complex operation due to various factors such, for example, a diverse building typology, is an important criterion (G1; G2; G3; G4): '*Such a complexity could lead to an attractive allocation of hydrogen*' (G4).

However, while the importance of several factors proposed by the researcher like a mix of construction years, building typologies [*relating to for example appartements or semi-detached homes*] or the number of addresses per building [*relating to the number of potential stakeholders in a renovation activity*] underlying the criterion have been validated by the focus group respondents (G1; G2; G3, G4), no comprehensive spatial demarcation has been brought forward by the respondents: *'Yes, these are several potential factors, but I think there are many more. And there are also some layers in between.'* (G2).

Reduction in natural gas consumption

While first labelled as 'CO_2-reduction', the focus group respondents (G1; G2; G4) expressed that measuring the actual reduction in CO_2-emission looking at all buildings in a certain neighbourhood has no reasonable chance: *'If you frame this as question about the buildings at the neighbourhood level, this is an almost impossible criterion, because CO_2-reduction is about where the energy comes from. So, that's about the source and then it becomes impossible to determine that at neighbourhood level.'* (G3). Respondent 2 elaborates on the complexity of this challenge by adding*: 'It depends on which source you take as starting point. You could even consider how much CO_2-emissions are realised by the construction of a windmill.'* (G2).

When trying to establish a quantifiable criterion, respondent 2 brought the amount of natural gas in cubic meters forward: *'What about the current natural gas use? Then we are not talking about how much [CO_2] is realised, but you choose between a neighbourhood with a high natural gas consumption or one with a very low consumption.'* (G2). Respondent 4 related the natural gas consumption then back to the CO_2-emissions by mentioning: *'Couldn't it be as follows: a neighbourhood consumes x number of cubic meters, which means that so much CO_2-emissions are realised by the combustion of it?'* (G4).

BOX 4: Criterion '*Complexity of conversion from natural gas to hydrogen as energy carrier*'
While in both the semi-structured interviews and the focus group an attempt was made to [*further*] define and spatially demarcate this criterion, due to the complexity of this inquiry no relevant findings can be reported on this. The following quotes describe the complexity of this issue:

- *'While thinking [the conversion] through or puzzling about it, we noticed that it is quite complex, that there is a lot involved.'* (I5), and while putting the conversion into context of repurposing the existing [*local gas*] infrastructure respondent 5 continues: *'in the overall picture, the use of existing infrastructure it is of course still a useful one. But it's not going to be a piece of cake. It's going to be hell of a job.'* (I5).

- *'This issue is very complex, and it depends on the neighbourhood you are looking at. We haven't come up with a standard model for this yet. (…). So, it really dependents on the situation, even on the street. You have to look from planning technical perspective at how you can pick up this like an oil slick that spreads slowly through the neighbourhood.'* (I7).

Nevertheless, this criterion has been included in the [*final*] pairwise comparison of the criteria due to its perceived relevance from a spatial-technical [*planning*] perspective.

5.2.4 Pairwise comparison of the criteria by focus group respondents

This section presents [*partly the]* results linked to the answer to sub-question 3: "*What are the relative weights for the different relevant criteria, explaining their importance in the overall decision-making?*". While the individual pairwise comparison (described in section 5.2.2) yielded next to unsatisfactory results also limited consensus on the weights and therefore relative importance of the different criteria, the second ronde of pairwise comparisons has been filled in by four experts present in the focus group after discussing the spatial demarcation of all relevant criteria here. Through an interim discussion with an AHP-expert, the way of presenting the pairwise comparison questions has been adjusted (see **appendix 4.5**). This issue is elaborated on the reflection chapter of this study (see section 7.2).

Table 5.3: Weights for criteria based on focus group participants

Criteria	**Weight of criteria**	**CR**
Complexity of conversion from natural gas to hydrogen (…)	17,8%	
Distance to future hydrogen infrastructure and sources	21,3%	
Percentage of monumental buildings	13,8%	
Social acceptance	20,7%	
Percentage of housing stock owned by housing cooperation	11,5%	
Reduction of natural gas	8,3%	
Complexity of large-scale insulating on ngh. scale	6,6%	13,7%

What can be observed from table 5.2 is that the consistency ratio between the individual answers of the four respondents is 13,7%. Therefore, the consistency lies outside the 10% threshold proposed by among others Saaty (2008) or Taherdoorst (2017).
Next to that, the relative importance of the different criteria can be extracted from the table. With 21,3% the distance to (future) infrastructure and sources has the highest weight relative to the other identified decision criteria, indicating that the distance [*between a neighbourhood and future infrastructure for or source of hydrogen*] is the most important criteria when considering in which neighbourhood the application of hydrogen is suitable. According to the combined expert judgement, the complexity of large-scale insulating on neighbourhood scale is least influential (6,6%) in this decision.

5.3 Main findings

The main findings from the semi-structured interviews, questionnaire and focus group elaborated on in this chapter so far are summarized below, per sub-question.

- For **hydrogen as energy carrier** an important role is foreseen in the built environment [*for heating purposes*] therefore in the **heat transition**, although the timing and the exact allocation areas are unclear.
- Except for the gas-fired boiler, all components and materials employed and processed in the gas distribution network on the local level [*including the in-house installation*] are from a **technical viewpoint** suitable for the **100% hydrogen transport** and able to meet current heating demands.
- **Seven criteria on the local level** relevant for informing a spatial decision-making model have been identified and validated by [*at least half of*] the experts (see box 3).
- The **relative weights per criterium** have been determined by first the combination of four individually filled in questionnaires (see **section 5.2.2**) and secondly again by a combination of four individually performed pairwise comparison after discussing the spatial demarcation in a focus group (**section 5.2.4**).
    - According to the combination of individual pairwise comparison **social acceptance** [*of hydrogen as an energy carrier*] is the most important factor in the decision-making, while the **percentage of housing owned by housing corporations** is the least important factor in the decision making
    - According to the collective pairwise comparison …
- With regard to the **spatial demarcation** of the criteria the results yielded mixed outcomes. While for some criteria like the percentage of housing stock owned by housing corporations and natural gas reduction rather clear demarcations could be established, the other criteria are subject to ambiguity due to underlying factors that need further [*place-specific*] demarcation.

6. Theoretical discourse and conclusion

In this chapter, the results derived in chapter 5 are critically discussed in relation to identified concepts **chapter 2 & 3**, in order to assess whether the research objectives formulated in **section 1.2** have been met. Consequently, answers to the connected sub-questions (**section 1.3**) are formulated. Lastly, the main research is answered (**section 6.2**) and implications for planning practice are elaborated on (**section 6.3**).

6.1 Discussion of sub-questions

Potential position of hydrogen as energy carrier in the heat transition of the built environment

The first sub-question of this research aims at identifying the potential position of hydrogen as energy carrier in the built environment. While **chapter 2** provides a comprehensive description of the potential applications of hydrogen in the built environment on the local scale, its capability to overcome the problem of intermittency, and its [*anticipated*] role in the built environment from a political perspective, **section 3.3** touches on the availability of [*to be repurposed*] infrastructure that could be used for its transportation. This section discusses whether the stakeholders recognize the [*above described*] potential and what actual spatial locations are foreseen.

Hydrogen is acknowledged as key component in the wider energy transition and therefore in the future energy supply system (CE Delft, 2017; NWP, 2022). For the position of hydrogen as energy carrier in the built environment the picture is less clear. While both literature (Gigler & Weeda, 2018; NWP; 2022; PBL, 2022) and the interview respondents foresee a potential position for hydrogen in the heat transition due to its ability to overcome intermittency problems (Clasteres, 2011) and the mismatch between [*spatial*] supply and demand patterns (Van Kaan, 2015), the lack of vast amounts of hydrogen now and in the near future [*for the built environment*] is highlighted as big uncertainty.
However, the possibility of repurposing infrastructure for hydrogen transport in the built environment as acknowledged by the interview respondents as well as by the identified literature (KIWA, 2018; CE Delft, 2017; Weeda & Niessink, 2020), is seen as an important asset for the future use of hydrogen as energy carrier in the built environment. Also, the possibility of hydrogen to be used as energy carrier in areas or buildings where other sustainable alternatives are not suitable contributes to the potential position of hydrogen in the heat transition (Hoogervorst, 2020; Weeda & Niessink, 2020), as argued also by the interview respondents (I2; I4; I6; I7; I9; I10). Overall, a spatial fragmentation of sustainable alternatives, including the application of hydrogen as energy carrier, is expected in the future (I6; I7; Weeda & Niessink, 2020).
Although not in line with the research scope of this study, both literature (Gigler & Weeda, 2018; PBL, 2020; Weeda & Niessink, 2020) and interview respondents (I2; I4; I5; I6; I7; I8; I10) highlight the importance of considering hydrogen as energy carrier not in isolation but in relation to the other sustainable alternatives (*'So I advocate for hydrogen in locations where it is [economically] wise, I advocate heat networks in locations where it is wise, and I advocate for all-electric solutions where it is wise. – R4).*

Answer to sub-question 1

"What is the potential position of hydrogen as energy carrier in the heat transition of the built environment?"

It can be concluded that, due to the prominent role that is foreseen for hydrogen in the future energy supply system and therefore its widespread spatial availability [*due to the presence of national-wide infrastructure and application in cluster 6-industry*] in Netherlands, hydrogen as energy carrier can fulfil a considerable position in the heat transition in the built environment, especially in parts of the existing building stock that are due to different constructional or spatial reasons not suitable for other sustainable alternatives. However, no conclusion can be drawn about the exact time and spatial location of its application because both are subject to the issue of (spatial) availability and cost.

Technical fitness of existing local gas transport infrastructure for hydrogen transport

Following the argument of Invernizzi et al. (2020) and Kempfert et al. (2022) repurposing strategies can play an important role in reduction of decommissioning of old infrastructure, in light of the waste management hierarchy by Lansink. Next to that, the repurpose of existing gas transport infrastructure [*on the local level*] is considered as a key aspect of emerging hydrogen networks (Speirs et al., 2018). While using the different components of the gas transport infrastructure [*on the local level*] are identified as being technical fit for hydrogen transport (KIWA, 2018), a conclusion on whether sufficient amounts of energy [*using hydrogen as carrier*] for heating purposes in the built environment is lacking. Therefore, this study aims at assessing whether such carrying capacity is present using the existing gas infrastructure.

Both in the theoretical and empirical part of this research, congruent evidence has been identified concerning the technical suitability of using the existing gas transport infrastructure on the local level for hydrogen transport. All components of the transport infrastructure system, starting from the regional entry point up to gas meter are suitable for the transport of 100% hydrogen, even without the need for any adjustments (KIWA, 2018; I1 – I8). All conventional materials used for pipes, except for gray cast iron and asbestos cement which are going to be replaced by 2024 (Enexis Netbeheer, n.d.; Liander, n.d.) or 2028 respectively (Stedin, n.d.), and in sleeves are suitable *('So, all of them can be used one-on-one for hydrogen transport'* – R2). Next to that, also the technical fitness of components installed into district stations, which reduce the pressure towards a level suitable for individual building use, for transporting hydrogen is confirmed by the respondents. While the mechanical setting of minor components like a spring might ask for a readjustment in the future, its repurposing potential from a technical point of view is confirmed ('*the components themselves are gas-tight and can therefore be reused'* – I5). The results from the interviews are in line with the theoretical framework, especially the findings from the KIWA-report (2018) which concludes "*it can therefore be said that the existing distribution networks are suitable for transporting hydrogen*" (2018, p. 34).

While with regard to sufficient carrying capacity of hydrogen transport through the existing distribution network the literature only discussed this theoretically based on the physical properties of thermal capacity (Haeseldonckx & D'haeseleer, 2007; Mischner, 2021), the results from the interviews (I2; I3; I4; I5; I7) highlight also the practical feasibility of transporting sufficient energy [*using hydrogen as energy carrier*] to meet heating demands in the built environment. Through an offset between the calorific value [*being three times lower for hydrogen than for natural gas*] and the density, the same amount of energy can be transported through the distribution network made possible through a threefold increase in speed (*'We haven't found any limitations there'* – I4).

Answer to sub-question 2

"To what extent is the existing gas transport infrastructure on the local scale from a technical perspective suitable for providing the required amount of energy in the built environment when using hydrogen as energy carrier for heating purposes?"

Based on the current technical insides derived at from various different pilot projects where hydrogen as energy carrier transported through existing gas distribution infrastructure for heating purposes in the built environment, it can be concluded that the existing gas transport infrastructure on the local level is suitable for the transporting sufficient energy using hydrogen as energy carrier to fulfil heating demands in the built environment.

Relevant criteria for the multi-criteria decision-making model

With the selection of an alternative, such as the appointment of a neighbourhood '*most'* suitable for hydrogen, requiring a trade-off between different considerations (Greene et al., 2011), spatial decision-making involves a large variety of feasible alternatives and multiple evaluation criteria (Malczewski, 2006). While criteria influencing the ultimate decision typically can't be maximized or be defined comprehensively (Belton & Stewart, 2002; Roy, 2005), the aim of the third sub-question was to identify [*potentially*] relevant criteria on the local level that inform the decision about which neighbourhood could be prioritized for the application of hydrogen as energy carrier. While **section 3.1.1** discusses different components of a socio-technical system underlying the current energy supply system for the built environment and in **section 2.2** the heat transition map [*of municipalities*], criteria that are relevant for the allocation for hydrogen as energy carrier in the built environment are currently lacking in the literature. Therefore, this research aimed at identifying relevant criteria on the local level.

While a socio-technical energy system is in general described as a technical core of physical artifacts interacting with a socio-cultural/-historical context (Ewertsson & Ingelstam, 2005) therefore consisting of a technical and a social component (Hughes, 1983; Trist & Bamforth 1951), relevant criteria on the local level pertaining to both the technical and social 'category' have been identified by the interview respondents. The interrelatedness, coined by Ropohl (1999) as "*the reciprocal interrelationship between humans and machines"* (1999, p. 186), between the different criteria was acknowledged by the interview respondents by highlighting that looking at technical criteria [*in relation to the existing gas distribution* *network*] only would lead to a one-sided outcome regarding the decision-making model. With existing energy systems, like the heating system of the built environment based on the combustion of natural gas, being characterized by the alignment between the technical and social network maintained by among others current consumer practices (Geels, 2019), the 'social acceptance of hydrogen as energy carrier' is identified as an important criterion by both the interview respondents (I4; I5; I6; I8; I9, I10) and the literature (Elbert, 2022; Gordon et al., 2022; McDowall, 2014). Next to that, both in the theoretical and in the empirical part of this study, an interesting similarity regarding another socio-institutional criterion has been identified. While based on the interview and focus group responses this was coined as the 'percentage of housing stock owned by housing corporations', indicating how much of the housing stock can be approached via one (or more, depending on the number of housing corporations active in a certain neighbourhood) stakeholder(s), the Expertise Centrum Heat (2021) lists this as 'contractability' (Dutch: contracteerbaarheid), described as "*in other words: are all homes individually owned or are many homes owned by one or a few housing corporations?*" (ECW 2021, p. 33).

When considering the technical components of a socio-technical energy system in a broad sense, different levels [*within the neighbourhood scale*] can be differentiated to facilitate further discussion of the criteria. Here a distinction is made between criteria that 'cover' a whole neighbourhood such as the distance between a neighbourhood and (future) hydrogen infrastructure or the reduction in natural gas consumption [*of a neighbourhood*] and criteria like monumental buildings that refer to single buildings but where the totality of all buildings matter on the neighbourhood scale.

On the neighbourhood scale the 'distance to (future) hydrogen infrastructure' was identified as important criterion, in order to ensure a secure supply of hydrogen. While the interview and focus group respondents highlighted this mainly from an availability viewpoint, the NWP (2022) highlights the economic benefit of the spatial proximity of (future) hydrogen infrastructure. Both the respondents (G1; G2; G3) and the literature (NWP, 2022; Gigler & Weeda, 2018) mentioned next to the distance to hydrogen infrastructure, also the distance to future industry clusters that could support the application of hydrogen as energy carrier in the built environment. This criterion presents a proper example for triangulation where a comprehensive understanding of a phenomena is developed by connecting findings from literature with multiple data collection methods.

In line with the Dutch climate agreement [*the amount of*] 'reduction in natural gas consumption' was identified as relevant criterion on the local level by both the interview and focus group respondents. However, specifically during the focus group discussion the issue of timing was highlighted here. Since the overall goal is phase out natural gas completely (Klimaatakkoord, 2019), the criterion of 'natural gas reduction' might be important at the start of the transition towards hydrogen as energy carrier in order to identify the first neighbourhood. A comparable criterion is not identified in the literature. While for example the PBL-analysis (2020) includes the potential CO2-reductions through a conversion to another sustainable heating alternative, these are linked to the national cost [*in €/ton CO2-reduction*] of each natural gas alternative. In the development of the envisioned decision-making model considering the actual CO2-reduction per neighbourhood when converting to hydrogen as energy carrier was labelled as undesired by the focus group respondents because of complexity ('Because CO2-savings is about where the energy comes from. So, that's about the source and the generation. Then it becomes impossible to determine that on the neighbourhood level.' – G3).

Looking at criteria on the neighbourhood that relate to single buildings, then 'monumental buildings' and the 'complexity of large-scale insulating on the neighbourhood scale' [*of the housing stock*] are identified as relevant criteria by the respondents. While the monumental buildings are also acknowledged in the literature as a criterion that can influence such a decision-making model (ECW, 2021; PBL, 2020), they are not listed as an individual criterion but placed together with other building characteristics, namely the construction year indicating the degree of suitable for insulation (ECW, 2021; NWP, 2022).

With 'complexity of large-scale insulating on the neighbourhood' being a rather ambiguous criterion therefore further discussed in **section 6.1.5**, a comparable criterion was not identified in the consulted literature. However, potential components of this criterion such as construction year and building typology are considered in the PBL-analysis (2020) as well.

Answer to sub-question 3

"What are relevant criteria on the local level potentially inform a spatial multi-criteria analysis for prioritizing suitable neighbourhoods for the application of hydrogen as energy carrier?"

While being acknowledged that it is not possible to establish a complete and comprehensive picture of all relevant criteria influencing the multi-criteria analysis for prioritizing suitable neighbourhoods for the application of hydrogen as energy carrier, seven criteria relevant on the local have been identified. Taking next to the semi-structured interviews also the findings from both the questionnaire and the focus group into account, the relevance of at least three criteria (complexity of conversion from natural gas to hydrogen, distance to future hydrogen infrastructure and sources, social acceptance) together explaining more than '60% of the overall decision' in the model (**section 4.3.5**) can be stated with confidence, based on the means of triangulation which was aimed at in this research (see figure 8 in **section 4.1**). Next to that, two exclusion criteria influencing the multi-criteria decision analysis for the allocation of hydrogen have been identified.

However, it should be noted that these criteria have been established based on a rather one-sided stakeholder perspective namely from a regional network provider point of view. In further refining of this decision-making model, other stakeholders in line with the argument of Greene et al. (2011) should be identified and consulted.

Relative importance of criteria in overall decision

According to the step 3 and 4 (**section 4.2.5**) for the development of a decision-making model following the AHP-approach by Saaty (2008), the fourth sub-question aimed at establishing the weights of each criterion and its subsequent relative importance in the overall decision.

Considering the explorative nature of this research topic, no discussion material could be found. Therefore, a discussion on the relative importance of the criteria in the overall decision retrieved from the pairwise comparison is not possible.

Answer to sub-question 4

“What are the relative weights for the different relevant criteria explaining their importance in the overall decision-making?”

Due to considerable differences in the responses from both the survey and the focus group, and based on remarks from the focus group respondents on the complexity inherent to a well-thought-out pairwise comparison of the different criteria, this study can’t provide a [*clear*] answer to this sub-question.

Spatial demarcation of relevant criteria

In order to utilize the relevant criteria that have been identified (see **section 5.2.1**) in a decision-making model encompassing a spatial context, aligning with sub-question 4 this research aims to spatially demarcate the criteria [*as far as possible*]. Hence, this section elaborates further on the ‘discussion’ [*between the focus group participants*] by considering identified literature on spatial demarcation of comparable criteria.
No discussion is provided on the ‘complexity of conversion from natural gas to hydrogen’.

Discussion: distance to (future) hydrogen infrastructure and sources
While the findings from focus group indicate the spatial demarcation of this criterion using the linear distance between a neighbourhood and (future) hydrogen infrastructure or source, taking ‘big’ spatial obstacles such a river into account, in particular one focus group respondent advocates taking also sub-criteria like the demand volume of an area into account. Although the identified literature (NWP, 2022; Weeda & Niessink, 2020) also consider the distance to ‘future supply’ as relevant, no further demarcation in a spatial sense is given.

Discussion: monumental buildings
In line with the consensus between the focus group respondents on the issue of different types of monumental buildings, the ECW (2021) also advocates for making no distinction between different types of monuments [*like national monuments and buildings with a protected city view*] because they consider the thermal shell of both types as being equal difficult to insulate. With regard to the quantification, the ECW (2021) highlights the importance of making an inventory of the monumental buildings with a list of neighbourhoods with ‘many’ monumental buildings but does not specific if this should be presented as number or percentage of the housing stock. Also, the PBL-analysis (2020) on gas-free neighbourhoods considers the presence of monumental buildings an important factor but doesn’t specify how the quantity is treated in further analysis.
The issue of relating the quantity of monumental buildings with the relative gas consumption of the whole neighbourhood highlighted by the focus group respondents is not discussed in the identified literature.

Discussion: Social acceptance
The importance of social acceptance for hydrogen as energy carrier was acknowledged by both the interview and focus group respondents and it scored the highest relative importance in both pairwise comparison rounds (see **section 5.2.2** & **5.2.4**) in line with several studies on

the heat transition in the Netherlands (Elbert, 2022; PBL, 2022; Weeda & Niessink, 2020). However, both the empirical part and the literature review haven't yielded any information on the spatial demarcation of this criterion. While Elbert (2022) touches upon certain socio-demographic characteristics (age, education, income) as potential indicators, these haven't been confirmed by the focus group respondents.

Discussion: Complexity of large-scale insulating on neighbourhood scale
The findings from the focus group indicate that this criterion consists of various sub-criteria, among others the variation in building age or building typology and others which are not identified yet (*'Yes, these are several potential factors, but I think there are many more. And there are also some layers in between.'* – G2).
While the, for example, the PBL-analysis (2020) also considers factors such as building age and building typology in their analysis, it is used to in another context here. Considered on the individual building scale, the difficulty of insulating a building to a certain energy label (B) and therefore being suitable for low-temperature heating is looked at.

Discussion: Reduction in natural gas consumption
While this research focussed on the transition from heating on natural gas to hydrogen therefore not considering situations where other energy carriers [*such as biomass*], this criterion focused exclusively on the reduction in natural gas consumption (and its subsequent CO_2-emission reduction). Considering also other energy carriers, the PBL-analysis (2020) discusses the reduction of all CO_2-emitting energy carriers, including natural gas, heating oil and biomass and the subsequent CO_2-emissions. While this therefore partly in line with the empirical evidence of this study, the PBL-analysis doesn't present this as unattached criterion but integrates it in the total national cost of CO_2-reduction which includes also a proximation of emissions released by extraction of an energy carrier (PBL, 2020; PBL; 2022).

Discussion: Percentage of housing stock owned by housing corporations
While this research identified specifically the percentage of housing stock owned by housing corporations as criterion which can be presented rather simply by spatial data, using for example data from the CBS 'kerncijfers wijken en buurten' (CBS, 2023) as an indicator for who many stakeholders within a neighbourhood need to be approached for a conversion (*'I think the point with housing corporations is that you can force some sort of uniformity regarding the solution. (…) You have some kind of power over choosing one standard solution for the entire neighbourhood'* – G3), the ECW (2021) does not only consider housing corporations but all kinds of ownerships in their quantification of stakeholders within a certain neighbourhood. However, regarding the spatial demarcation they also favour displaying it in percentages.

Answer to sub-question

"How can the identified criteria for the multi-criteria analysis be defined and spatially demarcated?"

Following from the above-presented discussion, the spatial demarcation of the identified criteria relevant for the multi-criteria analysis is subject to ambiguity. While it is possible to clearly spatial demarcate two of the seven criteria, namely the percentage of housing stock owned by housing corporations and the reduction of natural gas consumption [*within in a neighbourhood*], for the other five criteria no clear demarcation can be presented. Partly this has to do with the complexity inherent to the criteria, like for the 'complexity of conversion from natural gas towards hydrogen' where even the regional operator themselves still employ research for, and for the 'complexity of large-scale insulating on neighbourhood scale' and 'social acceptance' For the latter two an indicator consisting of various sub-criteria needs to be established.

While for the remaining two criteria [*monumental buildings; distance to (future hydrogen infrastructure and sources*] the sub-criteria have been established, the discussion yielded no final spatial demarcation which could be used in the [*subsequent*] application of the decision-making model.

6.2 Conclusion

While hydrogen as energy carrier is still acknowledged as a niche innovation for heating purposes in the built environment as because the state of development of infrastructure for hydrogen transport and trade markets for hydrogen, to name a few, are still in the pre-development phase in line with current literature (Smit et al., 2007), a considerable role in the heat transition of the built environment is foreseen in the future. Corresponding with the shortcomings of other sustainable alternatives for natural gas to deliver high-temperature heating, hydrogen as energy carrier can be applied in the areas that are characterized by either a diffuse spatial built-up, a considerable share of housing stock that is difficult to insulate or where the lack of space in the underground prevents the construction of additional infrastructure. Although the exact timing and spatial allocation of hydrogen is subject to uncertainty because of a [*current*] lack of availability in terms of volume and suitable transport infrastructure on the local level, this research identified corresponding with the latter issue the gas distribution infrastructure starting at the regional entry point up to the gas-fired boiler as technical suitable for the transport of 100% hydrogen to fulfil current heating demands. When taken together, the promising role of hydrogen as energy carrier in the built environment and the potential to repurpose existing gas infrastructure on the local level for hydrogen transport, both can be seen as important assets in the [*further*] decarbonization of the current energy supply system for the built environment.

Corresponding to the complexity inherent to decision-making in a spatial context, the findings of this research highlight the importance of making an integral assessment relating to the spatial allocation of hydrogen as energy carrier in the built environment because of the interaction between the various components such as user practices and technology that characterize the socio-technical regime of current energy infrastructure systems as identified by the multi-layer perspective (Kemp & Rip, 1998; Geels & Kemp, 2000).
While this research has been able to identify seven criteria relevant on the local level that can inform a decision-making model for the prioritization of neighbourhoods suitable for the application of hydrogen, the findings also made clear that these criteria are neither exclusive nor is a spatial demarcation comprehensively possible. Hence, the findings of this research, which have been socially co-constructed through expert discussion should be seen as starting point for stakeholders active in the heat transition of the built environment to elaborate upon further. Nevertheless, a multi-criteria analysis relating to sustainable energy planning can be seen as an interesting tool to divide complex decision-making into manageable components. Furthermore, taking the Dutch consensus-based planning culture into account the development of such a communication tool providers spatial planners with the opportunity to bring stakeholders with sometimes conflicting opinions together. Taking both the social construction of knowledge and the ability of such a decision-making model to function as a communication tool between stakeholders, this fits well in the ongoing planning discussion about the shift from rather technocratic planning practice towards more collaborative planning (De Roo, 2010; Proli, 2020; Sillak et al., 2021). The latter is characterized by consensus-based planning faced with uncertainty and complexity (De Roo, 2010; Innes, 2004) similar to the decision about where to apply hydrogen for heating purposes in the built environment investigated in this research. Therefore, it can be argued that the construction of knowledge about the potential allocation of hydrogen as energy carrier in the heat transition pertaining to the development of a decision-making model can contribute to a

socio-technical transition in the current energy infrastructure system based on the combustion of gas.

Lastly, the findings of this research offer valuable insights into shortcomings of the development of current heat transition maps by municipalities and other stakeholders. While existing neighbourhood boundaries (CBS-buurten) are used as a starting point for assigning sustainable heating alternatives to areas, the findings suggest that suitable alternatives [*including hydrogen as energy carrier*] don't restrain themselves to juridical boundaries.

6.3 Implications for planning practice

This research aimed at identifying relevant criteria on the local level that inform a multi-criteria decision analysis on the issue of developing a neighbourhood prioritization for the application of hydrogen as energy carrier for heating purposes in the built environment in order to support municipalities and other stakeholders in the heat transition. An understanding of the potential position of hydrogen as energy carrier in the heat transition and knowledge about the technical fitness of the existing gas distribution infrastructure is provided to municipalities and other actors involved in the implementation of the heat transition through this research. With the identification of suitable areas, namely where the construction of a district heating network is economically not feasible and full electrification of the housing stock is constructional not possible, more deliberated choices about the future repurposing of existing gas distribution infrastructure for the transport of hydrogen as energy carrier can decrease the need for premature decommissioning of energy infrastructure and the decarbonization of existing housing stock.
One of the main findings, namely the identification of seven relevant criteria informing a multi-criteria decision analysis, enables municipalities to develop a decision-making model for the prioritization of neighbourhoods suitable for hydrogen. While further enrichment of the model based on the municipal-specific context might be needed, the neighbourhood prioritization can support municipalities in the further development of their heat transition map and the subsequent implementation plans. The implementation plans of a neighbourhood that turn out be '*very suitable*' for the application of hydrogen as energy carrier might be postponed to a later moment when hydrogen is available on a larger scale and transport infrastructure in proximity is repurposed.

7. Reflections

The last chapter of this study is devoted to a reflection on the findings of this study (**section 7.1**), the methodological approach underlying this explorative study including its limitations (**section 7.2**), and on the overall research process regarding time management and the personal learning process (**box 5**). Lastly, recommendations for further research are suggested (**section 7.3**).

7.1 Findings

The findings of this research largely meet the research objectives (**section 1.1**) drawn up at the start of the research period in line with the research gap identified in the relevance of this study (**section 1.3**). A better understanding of the potential position of hydrogen as energy carrier in the built environment for heating purposes has been achieved. Together with a determination of the technical fitness of existing gas distribution infrastructure for hydrogen transport to meet heating demands in the built environment, the findings of this study might contribute to a strategic decision on where to repurpose existing gas distribution infrastructure for hydrogen transport in order to increase its lifespan and decrease the need for early decommission. As such, formulated implications for the planning practice (**section 6.3**) can contribute to the reduction of spatial impacts inherent to the 'biggest reconstruction' of the current energy supply system on the local level. However, while only touched upon implicitly the reciprocal relationship between hydrogen as energy carrier in the built environment and [*the potential of*] repurposing strategies for existing gas infrastructure (H1, see **section 3.5**) has not been established explicitly due to the uncertainties regarding both the spatial and time-wise application of hydrogen in the built environment.
With steering the allocation of scarce hydrogen as energy carrier [*in the built environment*] being a decision in complex spatial context, the finding of this research contributed to the body of knowledge relating to criteria that might influence such a decision on the local scale. However, while this explorative study was able to identify and spatially demarcate several criteria on the local level, it should be noted that these criteria are neither exhaustively nor exclusively related to hydrogen as sustainable alternative to natural gas.
Although, it can be justifiably argued that the findings of this research successfully achieved its research objectives therefore making it relevant for academia and society, the generalisation of these findings [*to every municipality in the Netherlands*] has been insufficiently investigated. Next to the fact that mostly experts from regional network providers have been included in the data collection, the geographical location within the Netherlands, the political colour of the sitting municipal government and prior decision relating to the energy landscape [*considering path-dependence*] might influence the opinion on hydrogen as energy carrier in general and the criteria influencing its spatial allocation.

In order to achieve more inclusive findings and therefore a more comprehensive picture of both the potential position of hydrogen as energy carrier in the heat transition and the criteria informing the decision-making model, the other [*main*] sustainable alternatives for natural gas could have been included into the research design. However, due to first the determined research scope [*which was largely based on the personal interest of the researcher*] and secondly time limitations. Another limitation regarding the findings is that while the criteria (except for one) have been defined and spatial demarcated, further elaboration on the underlying spatial data is needed before an actual geo-based multi-criteria analysis could be done. While this was part of the focus group aim due to time limitations this wasn't achieved.

Although being aware of several economic and political trends and developments, such the foreseen limited availability of hydrogen until around 2030 and the delay in construction of the national hydrogen infrastructure by the Gasunie, and therefore having in mind to formulate implications for planning practice for beyond 2030, the issue of 'time' or 'timing' n relation to the development of the decision-making model wasn't adequately addressed in neither the interviews nor the focus group, which resulted in unfocused answers by respondents and consequently ambiguous results.

7.2 Methodological approach

While the methodology of this research (**chapter 4**) justified the chosen research approach and outlined several points of attention for the applied data collection and analysis tools, several comments can be made in retrospect. As already highlighted in relation to the ethics (**section 4.4**), considering the positionality of the researcher in [*especially qualitative*] research is important (Wilson et al., 2022) since this can have an influence on the formulation of questions, interpretation of results and deduction of conclusions (Berger, 2015). In order to be transparent about position of the researcher, it is important to critically assess the above-mentioned points.

- Position of the researcher: Within all data collection techniques, the research could unintentionally steer the answers of the respondents. Especially during the semi-structured interviews and the focus group, physical attitude [*with regard to mimic and gestures*] and asking suggestive questions are examples of such behaviour. When checking the transcripts [*of especially the semi-structured interviews*] some examples of questions formulated in a nudging way have been identified. Hence, it could be the case that the researcher constrained the interview respondents in giving their own input.
- Subjectivity of the researcher: In making the selection for certain interview respondents, drafting the questions for both the semi-structured interviews and focus group, and analysing the transcripts, three moments could be identified at which the researcher determines which data is considered to be important for the research. Hence, there is a possibility relevant stakeholders or information is left out of the data collection. As identified already in section 4.4, the researcher is aware of its personal interest towards the rather 'technical' side of the heat transition and has a keen interest in the application of hydrogen as energy carrier in the built environment. This can be identified as a [*potential*] methodological limitation.
- Interpretation of results: While the data analysis was guided by clearly formulated research objectives (**section 1.1**) and demarcated by a specific research scope (**section 1.3**), this could have let to situation where 'other' relevant findings brought forward by the respondents was not given attention in the analysis of the findings and its subsequent interpretation. The researcher attempted to tackle this by conducting multiple rounds of coding the transcripts and comparing the outcomes of this.

- Deduction of conclusion: During the process of deducting the conclusion of a research, the researcher runs the risk of selecting certain results that eventually better fall in line with the relevance of the research and the personal conviction of the researcher related to the topic under study. While fully objectivity is not obtainable, the researcher declares no conflict of interest which could have influenced the conclusion.

Relating to the [*unsatisfactory*] results from the questionnaire a methodological limitation can be identified. The chosen approach for developing the multi-criteria analysis [*underlying the decision-making model*] could be described as complex and [*too*] difficult to outsiders in retrospect. While potentially having to do with the way of explaining the pairwise comparison by the researcher, various respondents expressed that the 'matrix' question (see **appendix 4.4**) was difficult to understand and therefore to fill in. As response to these remarks and in consultation with an AHP-expert (unstructured interview), the researcher changed the way of presenting the pairwise comparison leading to four reliable results [*in the form of four complete filled in pairwise comparison forms*] from the focus group respondents.
Reaching 100% response rate with both the questionnaire and the forms 'handed out' to the focus group participants at the end of the online meeting can be translated to high interest and commitment into the researchers topic.

Another point of attention important to highlight is the future-orientated nature of this research. While only sub-question two was concerned with present conditions [*of the technical fitness of existing gas distribution infrastructure for hydrogen transport*], all other questions were concerned with future situations. Therefore, it is important to be aware about the fact that statements made by the respondents can be subject to change. [*Unforeseen*] changes in the socio-technical landscape and regime through shock events or changes in political composition can influence perspectives of stakeholders.

Personal reflection on overall research process

Note: *To write a more persuasive and emphatic reflection on the personal experiences from the over research process, the following is written in first-person perspective*.
While the official start of the master thesis also considering the thesis proposal was somewhere in November 2022, my personal 'hydrogen as energy carrier' journey started already back in March 2022 when discovering a podcast from the Port of Rotterdam about the potential of hydrogen in our future energy supply system. From that moment on I knew that my master thesis would be about hydrogen as energy carrier in the built environment. Inspired by several projects about the heat transition in the built environment at my work at KAW architects and consultancy and being interested in the more technical side of converting a neighbourhood from natural gas towards a sustainable alternative, the idea for my final master thesis topic slowly evolved.

With having a rather clear idea about what I want to research, namely the technical feasibility of transporting hydrogen through existing gas infrastructure as starting point to [*as I see it*] further develop the PBL-analysis about 'natural gas free neighbourhoods', and whom I need and honestly want to speak, namely experts at different regional network providers to potential get the opportunity to visit a hydrogen-neighbourhood, I was able to make a flying start with my data collection. By the mid-March I already finished ten interviews. However, I experienced that ‘every’ climax is followed by less flowerily times. The first struggle I encountered during my thesis process was put things into writing. Dozens of transcript pages completely coded were staring at me every time I entered our home office. While having a comprehensive gantt-chart telling me exactly what I needed to when, it took me until May to properly start with the writing. Breaking up my planning in smaller bites, setting [*realistic*] daily goals and using other people to hold me accountable, I was able to tackle this struggle.

Another struggle running like a golden thread through nearly the entire thesis period was the trade-off between (a) ‘only’ developing the envisioned decision-making model or (b) also testing/illustrating it using GIS and a case study. While this consideration vastly influenced how the master thesis would be structured from the results section onwards and especially the formulation of the main research question, I was able to make a final decision on that finally by mid-May. Discussing this issue with my supervisor and others, taking the complexity inherent to the testing of the GIS-model and the imposed time limit of this research into account, led to the decision on developing the model as comprehensively as possible rather than testing an immature model with outcomes that run the risk of being subject to ambiguity.

By far the biggest struggle I encountered during different phases of my master thesis was to let go of my high ambitions and even higher standards I impose(d) on myself. Illustrating questions for this are: ‘Are 10 interviews really enough or shouldn’t I try to get more experts?’, ‘A document analysis as data collection technique would really have added value, wouldn’t it?’ or ‘Why would I need a plan B for the focus group?`. However, I would like to end with a positive note. My perseverance was appreciated by the respondents and yielded some very interesting contacts for the future. Furthermore, this research confirmed and fuelled my already-present interest in the energy transition and more specifically the heat transition in the built environment. In my future carrier I want to make societal impact by contributing to the spatial integration that is inherently linked to our energy supply system in transition, and the development of an energy supply system that enables the participation in society for everybody.

7.4 Recommendations for further research

Based on the conclusions presented in **chapter 6** and the reflection on both findings and the methodology outlined above, the following suggestions for further research on the position of hydrogen as energy carrier in relation to spatial decision-making in the heat transition of the built environment are made:

- While the aim of this research was [*only*] to develop a spatial decision-making model therefore to identify relevant criteria on the local level, its relative importance in the overall decision and a clear spatial demarcation, it would be valuable to actually test the model using a case study in order to assess whether a useful and realistic outcome is generated by this. Hence, it is suggested to apply the developed model on a municipality and discuss the subsequent neighbourhood prioritization with the experts interviewed.
- As Saaty (2008) suggests ‘all’ relevant stakeholders involved and affected by the decision should be mapped out in order to develop a coherent as possible overview

of all relevant criteria. Due to a limited resources especially time and a rather technical research scope, mostly experts working at different regional network providers have been included as interview and focus group respondents in the data collection. Hence, to arrive at a more coherent set of criteria it is suggested to query also other stakeholders active in the heat transition.

- While this research adopted the suggested 'magical number of 7 plus or minus 2' as a guideline for the number of criteria included in the development of the decision-making model, more criteria have been mentioned by the interview and focus group respondents that could be relevant on the local level. Next to that, the AHP-approach applied in this research allows for the establishment of multiple hierarchies of criteria. Therefore, using the possibility of developing multiple hierarchies in the AHP-approach further research could develop a more comprehensive set of relevant criteria accounting for the ambiguity inherent to some criteria
- In line with the research scope (**section 1.4**) this study focussed on hydrogen application as only sustainable alternative of natural gas combustion for heating purposes in the built environment on the individual building scale. Elaborating on a discussion point frequently brought forward by the respondents during both the interview and focus group, future research could include other sustainable alternatives next to hydrogen as well as central heating installations [such as boiler house of district heating network] next to neighbourhoods in the development of a decision-making model.
- Although touched upon in sub-question 2 and consequently elaborated on in the discussion section of this research, a more theoretical study on the potential of utilising the possibility to repurpose existing gas distribution infrastructure might offer interesting insights on where in the future hydrogen projects could develop.

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Appendix

4.1 Overview unstructured interview respondents

Respondent information	Date, location	Topics discussed
Dr. ir. J.J. Aué (Jan-Jaap), Researcher/project-manager at EnTranCe	10-01-2023, Zernikerlaan 17 Groningen	- Position of hydrogen in energy transition - Decision-making in heat transition - Potential factors influencing decision-making - Suggestions for interesting discussion partners & worthwhile papers/studies on hydrogen → Interview was completed with a small tour over the EnTranCe campus and visit of the hydrogen testing facilities
MSc. R. Niessink (Robin), Researcher Energy use in Built Environment, TNO	15-02-23, Online (Microsoft Teams)	- Position of hydrogen in energy/heat transition - Potential neighborhoods for hydrogen application - Decision-making in heat transition/energy planning - Potential factors influencing decision-making for hydrogen application - Suggestions for nteresting discussion partners & worthwhile papers/studies on hydrogen
BSc. F. v. d. Molen (Folckert) Researcher Climate, Air & Energy, PBL	14-02-23, Online (Microsoft Teams)	- Position of hydrogen in energy/heat transition (specifically in the PBL-analysis on 'Aardgasvrije wijken) - Potential neighborhoods for hydrogen application - Decision-making in heat transition/energy planning - Potential factors influencing decision-making for hydrogen application - Suggestions for nteresting discussion partners & worthwhile papers/studies on hydrogen

Dr. S. Elbert (Sarah), Researcher, Hanze University of Appl. Science	6-04-23, Zernikerlaan 17, Groningen	- Social acceptance for energy carrier, hydrogen specifically - Construction of indicator for social acceptance based on socio-demographic data - (Practical) experience with heat transition in Groningen
MSc. R. Calon (Ruben), Data specialist, Sweco Netherlands	25-03-23, Online (Microsoft Teams)	- Decision-making in spatial contexts - Multi-criteria decision analysis (specifically AHP) - Experience with execution of GIS-analysis - Discussion on presenting pairwise comparison
PhD. S. Jansz (Sascha), Researcher, Hanze University of Appl. Science	15-05-23, Online (Microsoft Teams)	- Tipps and literature suggestion for focus group - (Practical) experience with focus group execution
MSc. P. Leliveld, Researcher, KAW Architects and consultants	26-05-23, Kattenhage 1, Groningen	- Suitable data for relevant criteria (decision-making model) - (Practical) experience with GIS-analysis - Tips on data analysis in Excel

The [*brief*] interview notes and working session output [*for the focus group*] are available on request by sending an email to: Jonas.Vollbrandt@gmx.de.

4.2 Interview guides

Interview guide project manager, program manager & innovation manager (network providers): example interview respondent 1

Gespreksleidraad masterscriptie 'Waterstof in de gebouwde omgeving'

Opgesteld door:	Jonas Vollbrandt (masterstudent sociale planologie)
Methode:	1-op-1 diepte-interview
Gespreksduur:	+/- 60 minuten
Respondent:	Projectleider waterstofproefproject

Onderzoeksdoelstelling:
Het doel van dit onderzoek is inzicht te verkrijgen in het waterstofproject van de organisatie, en in de opzet en doelstelling van het project. Daarnaast is het van belang voor de onderzoeker de gedachtes en afweging van de locatiekeuze te achterhalen. Deze informeren het afwegingskader die de onderzoeker in de loop van de scriptie gaat ontwikkelen.

1. Introductie
- Welkom, voorstellen interviewer
- Toelichting onderzoeksopzet en -doelstelling
- Toelichting vertrouwelijkheid, terugkoppeling op gespreksverslag en geaggregeerde rapportage

2. Aanloop
- Introductie respondent (functie, verantwoordelijkheden, betrokkenheid project)
- Introductie organisatie (doel, activiteiten)
- Algemene kijk op toepassing van waterstof als energiedrager
  - Specifiek: toepassing in gebouwde omgeving / bestaande bouw
- Bestande waterstofprojecten binnen organisatie

3. Waterstofproject XXXXX
- Introductie en aanleiding van project
- Rol van organisatie en respondent in project
- Doel(-en) van het project
  - Vanuit organisatie-perspectief
  - Vanuit maatschappelijk-perspectief
- Verschillende projectfasen (inclusief tijdshorizon)
  - Huidige fase / stand van zaken van het project
- Uitdagingen/barrières
  - Thematisch: technisch, financieel en/of bouwkundig
  - In verschillende projectfasen

4. Afwegingskader
- Locatiekeuze voor XXXXX (ruimtelijk)
- Geschiktheid lokaal distributienetwerk gas (technisch)

- Keuze voor gebouwen (bouwtechnisch)
- Bijdrage aan CO2-reductie (milieukundig)

5. Afsluiting

Gesprekspunten geformuleerd in vragen

In het volgende deel zijn de bovengenoemde gesprekspunten uitgeschreven in vragen om een duidelijker beeld van de achterliggende gedachte van de gesprekspunten aan te geven. Afhankelijk van het antwoord van de respondent kunnen aanvullende/verdiepende vragen gesteld worden door de interviewer.

2. Aanloop

- Wat is uw functie binnen de organisatie en wat zijn uw verantwoordelijkheden?
- Hoe bent u betrokken geraakt bij het waterstofproject in ***********, en hoe lang bent u al bij dit project betrokken?
- Kunt u een korte toelichting geven op het bedrijf waar u werkt? Wat zijn de hoofdactiviteiten van uw organisatie en wat is het *(maatschappelijke)* doel wat uw organisatie nastreeft?
- Hoe kijkt uw organisatie naar de toepassing van waterstof als energiedrager? Welke rol speelt waterstof voor uw organisatie in de energietransitie?
    - Hoe kijkt uw organisatie naar de toepassing van waterstof als energiedrager in de gebouwde omgeving? Welke rol speelt waterstof voor uw organisatie in de warmtetransitie van de gebouwde omgeving *(richting CO2-neutraliteit in 2050?)?*
- Hoe kijkt u persoonlijk naar het toepassen van waterstof als energiedrager in het algemeen, en in de gebouwde omgeving?
- Wat zijn lopen project binnen uw organisatie die te maken hebben met waterstof?

3. Waterstofproject ***************

- Kunt u een algemene introductie/toelichting op/van het waterstofproject in *********** geven?
    - Wanneer is het project begonnen?
    - Welke partijen zijn naast uw organisatie betrokken bij het project?
    - Wie *(indien aangewezen)* is de hoofdverantwoordelijke van het project?
- Hoe is het waterstofproject in *********** tot stand gekomen?
    - Wat was de aanleiding van het project?
    - Wie was de initiatiefnemer van het project?
- Wat is de rol van uw organisatie binnen het project?
    - Welke activiteiten en verantwoordelijkheden houdt dit in?
- Wat is uw eigen rol binnen het project?
    - Welke activiteiten en verantwoordelijkheden brengt dit met zich mee?
- Wat is het doel / wat zijn de doelen van het project?
    - Hebben verschillende partijen verschillende doelen geformuleerd?
    - Wat is het beoogde doel voor uw organisatie?
- Wat zijn de verschillende fasen van dit project?

    - Wat is de huidige fase van het project?
- Wat zijn uitdagingen/barrières waar het project tegen aanloopt oftewel tegen aanliep?
    - Waren deze uitdagingen technisch, bouwkundig of financieel van aard?
    - In welke projectfasen liep/loopt men tegen welke uitdagingen aan?
- Hoe zijn potentiële uitdagingen verholpen worden?

4. Afwegingskader

De onderzoeker gaat binnen zijn masterscriptie een afwegingskader ontwikkelen om te komen tot een prioritering van wijken waar de inzet van waterstof als energiedrager '*meer* ***en*** *minder'* geschikt is op basis van een aantal criteria (ingedeeld in de categorieën: technisch-ruimtelijk, bouwkundig en milieukundig). Hiervoor is het interessant en belangrijk de afwegingen te achterhalen die geleid hebben tot de locatiekeuze van het waterstofproject in ***********.

- Hoe is de locatiekeuze voor *********** tot stand gekomen?
    - Welke afwegingen zijn gemaakt bij de locatiekeuze?
    - Welke ruimtelijke argumenten spraken voor **en** tegen *********** als locatie oor het waterstofproject?
- *(Indien van toepassing:)* In hoeverre heeft de geschiktheid van het lokale distributienet een rol gespeeld bij de locatie?
- Wat voor (*type*) gebouwen zijn aangesloten bij het waterstofproject / op het waterstofdistributienetwerk?
    - Welke afwegingen **vanuit uw organisatie** zijn gemaakt bij het type gebouw(en)?
    - Welke bouwkundige argumenten spraken voor **en** tegen bij bepaalde (*type*) gebouwen?
- In hoeverre heeft de (*vooraf theoretisch berekende; in de praktijk daadwerkelijke)* CO_2-reductie door de overstap van aardgas naar groene waterstof een rol gespeeld bij de keuze voor de locatie en het type gebouw?

5. Afsluiting

Interview guide asset manager (network provider): example interview respondent 5

Gespreksleidraad masterscriptie 'Waterstof in de gebouwde omgeving'

Opgesteld door:	Jonas Vollbrandt (masterstudent sociale planologie)
Methode:	1-op-1 diepte-interview
Gespreksduur:	+/- 60 minuten
Respondent:	Netstrateeg gas of vergelijkbare technische functie

Onderzoeksdoelstelling: Het doel van het onderzoek is meervoudig. In het eerste gedeelte wordt de opbouw en werkwijze van het huidige gasnet evenals de technische haalbaarheid van 100% transport door het lokale distributienet onderzocht. Het twee gedeelte heeft als doel om 'technisch-ruimtelijke' criteria (in relatie tot het gasnet) in kaart te brengen die relevant zijn voor een afwegingskader en deze vervolgens te rangschikken naar relevantie.

1. Introductie

- Welkom, voorstellen interviewer
- Toelichting onderzoeksopzet en -doelstelling
- Toelichting vertrouwelijkheid, terugkoppeling op gespreksverslag en geaggregeerde rapportage

2. Aanloop

- Introductie respondent (functie, verantwoordelijkheden)
    - Specifiek: in relatie tot gasnetten (lokaal)
- Introductie organisatie (doel, activiteiten)
- Algemene kijk op toepassing van waterstof als energiedrager
    - Specifiek: toepassing in gebouwde omgeving / bestaande bouw
- Betrokkenheid waterstofprojecten binnen organisatie

3. Lokale gasnet en geschiktheid voor waterstof

- Opbouw/werkwijze (huidig) lokaal gasnet
    - Onderdelen tot aan woning
- Geschiktheid distributienet voor 100% waterstof
    - Theoretisch/praktisch
- Nodige aanpassingen aan infrastructuur
    - Onderdelen distributienet
    - Onderdelen in woning
- Gevolgen van waterstoftransport voor werking distributienet
    - Onderzoeker denkt zelf aan:
        - Lager moleculairgewicht
        - Lager calorische waarde
        - Invloed op materialen
        - Transportcapaciteit
        - Verontreiniging leidingen
- Technische uitdagingen bij waterstof transport door huidig distributienet
    - Oplossingen voor uitdagingen

4. Afwegingskader op wijkniveau

Ervan uitgaand dat er geen technische belemmeringen zijn bij het transport van 100% waterstof door het huidige distributienet (van regionaal ingangspunt tot aan de gasmeter) en vervolgens elke woning (waar een gasnet ligt) theoretisch voorzien kan worden van waterstof is het doel van de onderzoeker erachter te komen waar de inzet van waterstof als energiedrager in de gebouwde omgeving *meer of minder* geschikt is. Het onderzoek zal leiden tot een afwegingskader (geo-based beslissingsmodel) voor een prioritering van wijken.

- Open vraag naar relevant criteria
- Aanwezigheid gasnet
    - Graden/mate van geschiktheid distributienet
- Vervangingsstrategieën
    - Onderhoudsactiviteiten
    - Planning
- Afstand tot regionaal ingangspunt/invoerpunt
- Lengte gasleiding binnen een wijk
    - Opslagcapaciteit (line-pack)
    - Hoeveelheid aanpassing (in meters, aantal onderdelen)
- Complexiteit omzetting van aardgas naar waterstof
- Rangschikking van criteria (weging per criteria)

Gesprekspunten geformuleerd in vragen

In het volgende zijn de bovengenoemde gesprekspunten uitgeschreven in vragen om een duidelijker beeld van de achterliggende gedachte van de gesprekspunten te geven. Afhankelijk van het antwoord van de respondent kunnen aanvullende/verdiepende vragen gesteld worden door de interviewer.

1. Introductie

- Welkom, voorstellen interviewer
- Toelichting onderzoeksopzet en -doelstelling
- Toelichting vertrouwelijkheid, terugkoppeling op gespreksverslag en geaggregeerde rapportage

2. Aanloop

- Kunt u zich kort voorstellen?
    - Wat is uw functie binnen het bedrijf en welke taken en verantwoordelijkheden horen hierbij?
- Hoe kijkt u persoonlijk naar het toepassen van waterstof als energiedrager in het algemeen, en in de gebouwde omgeving?
- Welke rol speelt waterstof als energiedrager volgens u binnen de warmtetransitie van de gebouwde omgeving?
- Hoe kijkt uw organisatie tegen de toepassing van waterstof als energiedrager aan?

    - Hoe kijkt uw organisatie tegen de toepassing van waterstof in de gebouwde omgeving aan?
- Bent u betrokken bij huidige waterstofprojecten binnen uw organisatie?
    - Wat is uw rol binnen deze projecten?

3. Lokale gasnet en geschiktheid voor waterstof

- Hoe is het huidige lokale distributienet voor gas opgebouwd (*in het algemeen*)?
    - Wat zijn de verschillende onderdelen van het lokale gasnet tot aan de woning?
- Kunt u op basis van de opbouw van het lokale distributienet een korte toelichting geven over de werkwijze van het gasnet?
    - Welke rol spelen de verschillende onderdelen van het gasnet bij de levering van gas (*gekeken vanuit het regionale ingangspunt tot aan de meter in de woning*)?
- Is het huidige distributienet voor gas geschikt voor het transport van waterstof?
    - In hoeverre is het gasnet en de onderdelen hiervan geschikt voor het transport van 100% waterstof tot aan de woning?
    - In hoeverre zou het bestaande lokale distributienet de huidige warmtevraag van de bestaande bouw (*op wijkniveau*) kunnen bedienen bij inzet van 100% waterstof?
- Welke aanpassingen aan het huidige distributienet zijn nodig om 100% waterstof tot aan de woning (*/tot aan de gasmeter*) te leveren bij gelijkblijvende warmtevraag?
    - Om welke onderdelen van het gasnet gaat het en wat zijn de technische aanpassingen?
    - In hoeverre kunnen dergelijke aanpassingen gedaan worden tijdens vervangingsactiviteiten/onderhoud van het gasnet?
- Welke aanpassingen in de woning zijn nodig voor het transport (*tot aan de ketel*) **en** het gebruik van 100% waterstof in de woning?
- Welke gevolgen voor de werking heeft het transport van 100% waterstof door het huidige (*wellicht aangepaste*) distributienet?
    - Zijn er effecten/gevolgen waar m.b.t. de leveringszekerheid van klanten rekening mee gehouden moet worden?
- Welke technische uitdagingen bij het aanpassen van het huidige distributienet voor het transport van waterstof tot aan de woning, **en** bij het transport van 100% waterstof zijn binnen waterstofprojecten binnen uw organisatie komen kijken?
    - Hoe is men hiermee omgegaan/hoe heeft men deze uitdagingen opgelost?

4. Afwegingskader op wijkniveau

- Gekeken naar de onderzoeksdoelstelling van de student, wat zijn volgens u relevante technisch-ruimtelijke criteria (*in relatie tot het distributienet*) die van belang zijn bij het ontwikkelen van een dergelijk afwegingskader?
- Hoe denkt u over de volgende criteria?
    - Zijn er **gradaties van geschiktheid** voor het transport van 100% waterstof door het bestaande gasnet (*gekeken naar het **type materiaal***)?
    - In hoeverre kunnen vervangingsstrategieën (*onderhoudsactiviteiten, moment van onderhoud*) een rol spelen?

- Welke rol speelt de **afstand** (*van de wijk*) tot aan het **regionaal ingangspunt** (oftewel een **invoerlocatie**) een rol?
  - Kunnen individuele wijken voorzien worden van waterstof zonder de levering van gas aan andere wijken te beïnvloeden?
- In hoeverre speelt de **lengte** van de gasleiding (*binnen een wijk)* een rol?
  - Opslagcapaciteit (line-pack)
  - Hoeveelheid aanpassing (in meters, aantal onderdelen)?
- Hoe kijkt u naar de **complexiteit** die komt kijken bij de omzet van aardgas naar waterstof binnen een gebied?
  - Zijn er gradaties van complexiteit gekeken naar de opzet van een gasnetwerk binnen een wijk?
  - Zijn er binnen Alliander strategieën/ideeën hoe men met de omzet van aardgas naar waterstof kan omgaan?

Interview guide project leader (municipality): example interview respondent 9

Gespreksleidraad masterscriptie 'Waterstof in de gebouwde omgeving'

Opgesteld door:	Jonas Vollbrandt (masterstudent sociale planologie)
Methode:	1-op-1 diepte-interview
Gespreksduur:	+/- 60 minuten
Respondent:	Projectleider waterstofproefproject

Onderzoeksdoelstelling:
Het doel van dit onderzoek is inzicht te verkrijgen in het waterstofproject van de organisatie, en in de opzet en doelstelling van het project. Daarnaast is het van belang voor de onderzoeker de gedachtes en afweging van de locatiekeuze te achterhalen. Deze informeren het afwegingskader die de onderzoeker in de loop van de scriptie gaat ontwikkelen.

1. Introductie
- Welkom, voorstellen interviewer
- Toelichting onderzoeksopzet en -doelstelling
- Toelichting vertrouwelijkheid, terugkoppeling op gespreksverslag en geaggregeerde rapportage

2. Aanloop
- Introductie respondent (functie, verantwoordelijkheden, betrokkenheid project)
- Introductie organisatie (doel, activiteiten)
- Kijk op toepassing van waterstof als energiedrager
    - Specifiek: toepassing in gebouwde omgeving / bestaande bouw
- Positie van waterstof in warmtetransitie

3. Waterstofproject *********, *************
- Introductie en aanleiding van project
- Rol van organisatie en respondent in project
- Doel(-en) van het project
    - Vanuit organisatie-perspectief
    - Vanuit maatschappelijk-perspectief
- Verschillende projectfasen (inclusief tijdshorizon)
    - Huidige fase / stand van zaken van het project
- Uitdagingen/barrières
    - Thematisch: technisch, financieel en/of bouwkundig
    - In verschillende projectfasen

4. Afwegingskader
- Locatiekeuze voor ***********, *********** (ruimtelijk)
- Geschiktheid lokaal distributienetwerk gas (technisch)
- Keuze voor gebouwen (bouwtechnisch)
- Bijdrage aan CO_2-reductie (milieukundig)

5. Afsluiting

Gesprekspunten geformuleerd in vragen

In het volgende deel zijn de bovengenoemde gesprekspunten uitgeschreven in vragen om een duidelijker beeld van de achterliggende gedachte van de gesprekspunten aan te geven. Afhankelijk van het antwoord van de respondent kunnen aanvullende/verdiepende vragen gesteld worden door de interviewer.

2. Aanloop

- Wat is uw functie binnen de organisatie en wat zijn uw verantwoordelijkheden?
- Hoe bent u betrokken geraakt bij het waterstofproject in *********** (***********), en hoe lang bent u al bij dit project betrokken?
- Kunt u een korte toelichting geven op het bedrijf waar u werkt? Wat zijn de hoofdactiviteiten van uw organisatie en wat is het *(maatschappelijke)* doel wat uw organisatie nastreeft?
- Hoe kijkt u persoonlijk naar het toepassen van waterstof als energiedrager in het algemeen, en in de gebouwde omgeving?
- Welke rol speelt waterstof als energiedrager volgens u binnen de warmtetransitie van de gebouwde omgeving?
- Zijn er naast het waterstofproject in *********** nog andere project met waterstof binnen uw gemeente? Zo ja, welke?

3. Waterstofproject *********, *************

- Kunt u een algemene introductie/toelichting op/van het waterstofproject in *********** geven?
    - Wanneer is het project begonnen?
    - Welke partijen zijn naast uw organisatie betrokken bij het project?
    - Wie *(indien aangewezen)* is de hoofdverantwoordelijke van het project?
- Hoe is het waterstofproject in *********** (***********) tot stand gekomen?
    - Wat was de aanleiding van het project?
    - Wie was de initiatiefnemer van het project?
- Wat is de rol van uw organisatie binnen het project?
    - Welke activiteiten en verantwoordelijkheden houdt dit in?
- Wat is uw eigen rol binnen het project?
    - Welke activiteiten en verantwoordelijkheden brengt dit met zich mee?
- Wat is het doel / wat zijn de doelen van het project?
    - Hebben verschillende partijen verschillende doelen geformuleerd?
    - Wat is het beoogde doel voor uw organisatie?
- Wat zijn de verschillende fasen van dit project?
    - Wat is de huidige fase van het project?
- Wat zijn uitdagingen/barrières waar het project tegen aanloopt oftewel tegen aanliep?
    - Waren deze uitdagingen technisch, bouwkundig of financieel van aard?
    - In welke projectfasen liep/loopt men tegen welke uitdagingen aan?
- Hoe zijn potentiële uitdagingen verholpen worden?

4. Afwegingskader

De onderzoeker gaat binnen zijn masterscriptie een afwegingskader ontwikkelen om te komen tot een prioritering van wijken waar de inzet van waterstof als energiedrager '*meer **en** minder'* geschikt is op basis van een aantal criteria (ingedeeld in de categorieën: technisch-ruimtelijk, bouwkundig en milieukundig). Hiervoor is het interessant en belangrijk de afwegingen te achterhalen die geleid hebben tot de locatiekeuze van het waterstofproject in ***********, ***********.

- Hoe is de locatiekeuze voor *********** (***********) tot stand gekomen?
  - Welke afwegingen zijn gemaakt bij de locatiekeuze?
  - Welke ruimtelijke argumenten spraken voor **en** tegen *********** als locatie oor het waterstofproject?
- Hebben de karakteristieken van het gasnet (nationaal, regionaal) een rol gespeeld bij de locatie van *********** als proeflocatie?
  - *(Indien van toepassing:)* In hoeverre heeft de geschiktheid van het lokale distributienet een rol gespeeld bij de locatie?
- Wat voor (*type*) gebouwen zijn aangesloten bij het waterstofproject / op het waterstofdistributienetwerk?
  - Welke afwegingen **vanuit uw organisatie** zijn gemaakt bij het type gebouw(en)?
  - Welke bouwkundige argumenten spraken voor **en** tegen bij bepaalde (*type*) gebouwen?
- In hoeverre heeft de (*vooraf theoretisch berekende; in de praktijk daadwerkelijke)* CO_2-reductie door de overstap van aardgas naar groene waterstof een rol gespeeld bij de keuze voor de locatie en het type gebouw?

Interview guide program manager (***************)

Gespreksleidraad masterscriptie 'Waterstof in de gebouwde omgeving'

Opgesteld door:	Jonas Vollbrandt (masterstudent sociale planologie)
Methode:	1-op-1 diepte-interview
Gespreksduur:	+/- 60 minuten
Respondent:	Programmamanager Energie (Stadsontwikkeling, **************)

Onderzoeksdoelstelling:
Het doel van dit onderzoek is inzicht te verkrijgen in de (potentiële) positie van waterstof in de warmtetransitie van de gebouwde omgeving, de toepasbarheid van deze (2^{de} orde) energiedrager en kansrijke gebieden binnen de gemeente Groningen. Daarnaast is het van belang voor de onderzoeker om tot relevante criteria te komen die, een afwegingskader met een prioritering van wijken als outcome informeren. De gemeente Groningen wordt hiervoor als casus gebruikt.

1. Introductie
- Welkom, voorstellen interviewer
- Toelichting onderzoeksopzet en -doelstelling
- Toelichting vertrouwelijkheid, terugkoppeling op gespreksverslag en geaggregeerde rapportage

2. Aanloop
- Introductie respondent (functie, verantwoordelijkheden)
- Introductie organisatie, afdeling Stadsontwikkeling (doel, activiteiten)
- Kijk op toepassing van waterstof als energiedrager
    - Specifiek: toepassing in gebouwde omgeving/ bestaande bouw
- Potentiële positie van waterstof in de warmtetransitie (**algemeen**)

3. Waterstof in de gemeente ***************
- Positie waterstof binnen de warmtetransitie van gemeente **********
    - Specifiek: binnen het warmtetransitieplan (uitvoeringsplan)
    - Specifiek: in relatie tot andere duurzame alternatieven
    - Specifiek: mogelijke toepassing bij hybride oplossingen
- Waterstof als transitiegas richting 2050 (als tijdelijke oplossing)
- Kansrijke buurten voor inzet waterstof (**theoretisch**)

4. Afwegingskader
- Open vraag naar relevante criteria
- Locatiekeuze voor inzet van waterstof (ruimtelijk)
- Keuze voor gebouwen (bouwtechnisch)
- Bijdrage aan natuur en milieu (milieukundig)
- Laagste maatschappelijke kosten (financieel)
- Sociale aspecten (bijvoorbeeld: draagvlak, maatschappelijk acceptatie)
- Koppelkansen met wijkvernieuwings-/uitvoeringsplannen

5. Afsluiting

Gesprekspunten geformuleerd in vragen

In het volgende deel zijn de bovengenoemde gesprekspunten uitgeschreven in vragen om een duidelijker beeld van de achterliggende gedachte van de gesprekspunten aan te geven. Afhankelijk van het antwoord van de respondent kunnen aanvullende/verdiepende vragen gesteld worden door de interviewer.

2. Aanloop

- Wat is uw functie binnen de organisatie en wat zijn uw verantwoordelijkheden?
- Kunt u een korte toelichting geven op de afdeling waar u werkt? Wat zijn de hoofdactiviteiten van uw afdeling en wat is het *(maatschappelijke)* doel wat uw afdeling stadsontwikkeling nastreeft?
- Hoe kijkt u op de toepassing van waterstof als energiedrager in het algemeen?
  - Specifiek: toepassing in de gebouwde omgeving?
- Wat is volgens u de (*potentiële*) positie van waterstof als energiedrager in de warmtetransitie?
- Heeft u binnen uw functie als programmamanager te maken met de toepassing van waterstof?

3. Waterstof in de gemeente **********
- Kunt u voor mij de positie van waterstof als energiedrager in de warmtetransitie van de gemeente Groningen schetsen?
  - Specifiek: de positie van waterstof binnen het warmtetransitieplan (2022-2030) en de tot heden opgestelde uitvoeringsplannen?
  - Specifiek: de positie van waterstof in relatie tot de andere duurzame aardgasalternatieven (*All-electric, warmtenet, groen gas*)?
  - Specifiek: de positie van waterstof bij hybride oplossingen waar een cv-ketel de piek van warmtevraag (*met name op koude dagen*) opvangt?
- Hoe kijkt u naar de potentie van waterstof als tijdelijke oplossing, oftewel als transitiegas voor de klimaatdoelen van de gemeente Groningen?
  - Specifiek: CO2-neutraal in 2035
- Kunt u (*zo veer mogelijk*) onafhankelijk van de gemeentelijke kijk op de toepassing van waterstof in de gebouwde omgeving kansrijke buurten voor de (**theoretische**) inzet van waterstof als energiedrager uitlichten?
  - Zijn buurten wel het geschikte schaalniveau voor aardgasvrije oplossingen?
  - Wat zijn belangrijke afwegingen bij het kiezen van het schaalniveau?
- Kunt u een korte toelichting op het uitvoeringsprogramma aardgasvrije wijken geven?

4. Afwegingskader
"We hebben zonet al gesproken over kansrijke buurten in het algemeen. In het volgende deel van dit interview wil ik graag verder het beoogde afwegingskader induiken. Tot nu toe doelde ik op een drietal criteria (technisch-ruimtelijk, bouwkundig en milieukundig). Op basis van de gesprekken die ik tot nu toe heb gevoerd, ben ik er echter van overtuigd dat een verbreding van de criteria handig oftewel noodzakelijk is. Per categorie heb ik een aanzet van potentiële criteria gedaan en wil deze graag met u bespreken."

- Wat zijn volgens u relevante criteria die bij een degelijk afwegingskader van belang kunnen zijn, en die de prioritering op wijkniveau kan beïnvloeden?
    - Beschikbaarheid van waterstof
    - Verhouding tot andere duurzame alternatieven (in het kader van de warmtetransitiekaart)
- Welke afwegingen oftewel **ruimtelijke** argumenten zijn van belang bij de locatiekeuze?
    - Afstand tot nationale backbone (GasUnie)
    - Opwekmogelijkheden in de buurt (bijvoorbeeld op industrieterrein)
    - Uitvoerbaarheid: loskoppelen van bestaand net i.r.t. leveringszekerheid
    - Aantal aansluitingen in gebied
- Wat voor **type gebouwen** zijn het meest geschikt, oftewel komen gekeken naar andere alternatieven in aanmerking?
    - Oude binnensteden (geen ruimte in de ondergrond, overlast aanleg)
    - Monumentale (/oude) panden (complexe verduurzamingsvraag)
    - Diffuse bebouwing (hoge maatschappelijk kosten aanleg infra)
    - Diverse bebouwing (complexe verduurzamingsvraag)
- Welke **milieukundige afwegingen** kunnen van belang zijn bij het prioriteren van gebieden?
    - CO_2-reductie op basis van warmtevraag (huidig fossiel energieverbruik)
    - Luchtvervuiling door graafwerkzaamheden (aanleg warmtenet, verzwaring elektriciteitsnet en plaatsen van meterkastjes)
- Welke **sociale aspecten** komen bij de warmtetransitie oftewel de wijkenergieplannen kijken die van invloed kunnen zijn bij de prioritering (*ook in relatie tot tijdshorizon*)?
    - Draagvlak/maatschappelijke acceptatie van aardgasalternatief
    - Percentage woningvoorraad in corporatiebezit
    - Energiecorporatie aanwezig in gebied (early adopters)
- Hoe zouden bestaande/bekende wijkvernieuwings- oftewel uitvoeringsplannen van de gemeente (*in overleg met partners zoals de woningcorporaties*) van belang kunnen zijn bij een degelijke prioritering op wijkniveau?

Interview guide program adviser energy and heat (********)

Gespreksleidraad masterscriptie 'Waterstof in de gebouwde omgeving'

Opgesteld door: Jonas Vollbrandt (masterstudent sociale planologie)
Methode: 1-op-1 diepte-interview
Gespreksduur: +/- 60 minuten
Respondent: Waterstofexpert (***********)

Onderzoeksdoelstelling:
Het doel van dit onderzoek is inzicht te verkrijgen in de potentiële positie van waterstof in de gebouwde omgeving, de toepasbaarheid van deze (2de orde) energiedrager en kansrijke gebieden voor het inzet. Daarnaast is het van belang voor de onderzoeker om tot relevante criteria (categorieën: technisch-ruimtelijk, bouwkundig, milieukundig) te komen die het afwegingskader informeren kunnen.

1. Introductie
- Welkom, voorstellen interviewer
- Toelichting onderzoeksopzet en -doelstelling
- Toelichting vertrouwelijkheid, terugkoppeling op gespreksverslag en geaggregeerde rapportage

2. Aanloop
- Introductie respondent (functie, verantwoordelijkheden)
- Introductie organisatie (doel, activiteiten)
- Kijk op toepassing van waterstof als energiedrager
    - Specifiek: toepassing in gebouwde omgeving/ bestaande bouw
- Ervaring met waterstofprojecten/-initiatieven

3. Positie van waterstof in warmtetransitie
- Potentiële positie in relatie tot andere duurzame alternatieven
- Uitdagingen bij toepassing van waterstof
- Kansrijke buurten voor waterstof (algemeen)
    - Geschikt schaalniveau

4. Afwegingskader
- Open vraag naar relevante criteria
- Locatiekeuze voor inzet van waterstof (ruimtelijk)
    - Afwegingen bij locatiekeuze
    - Ruimtelijke argumenten voor/tegen locatie
- Keuze voor gebouwen (bouwtechnisch)
    - Type gebouwen (geschikt voor MT/HV)
    - Typologie
- Bijdrage aan milieudoelstellingen (milieukundig)
    - CO2-reductie
    - Luchtvervuiling door aanpassing infrastructuur/installaties
- Sociale aspecten

Gesprekspunten geformuleerd in vragen

In het volgende deel zijn de bovengenoemde gesprekspunten uitgeschreven in vragen om een duidelijker beeld van de achterliggende gedachte van de gesprekspunten aan te geven. Afhankelijk van het antwoord van de respondent kunnen aanvullende/verdiepende vragen gesteld worden door de interviewer.

2. Aanloop

- Wat is uw functie binnen de organisatie en wat zijn uw verantwoordelijkheden?
  - In hoeverre heeft u te maken met waterstof binnen uw organisatie?
- Kunt u een korte toelichting geven op het bedrijf waar u werkt? Wat zijn de hoofdactiviteiten van uw organisatie en wat is het *(maatschappelijke)* doel wat uw organisatie nastreeft?
- Hoe kijkt u op de toepassing van waterstof als energiedrager in het algemeen?
  - Specifiek: toepassing in de gebouwde omgeving?
- Wat is volgens u de positie van waterstof als energiedrager in de energietransitie?
- Wat zijn lopende projecten binnen uw organisatie die te maken hebben met waterstof?
  - Wat zijn uw eigen ervaringen met waterstofprojecten?

3. Positie van waterstof in warmtetransitie
"We hebben zonet de positie van waterstof in de energietransitie belicht en u heeft een toelichting gegeven over de potentiële toepassingen van waterstof als energiedrager in de gebouwde omgeving gegeven. Nu wil ik graag specifiek op de warmtetransitie inzoomen."

- Wat is volgens u de positie van waterstof als energiedrager in de warmtetransitie van de gebouwde omgeving?
  - Wat zijn voor- en tegenargumenten voor de toepassing van waterstof in de gebouwde omgeving?
- Gekeken naar andere duurzame aardgasalternatieven, wat is de potentiële positie van waterstof in relatie tot deze alternatieven?
  - Hoe denkt u over de positie van waterstof met oog op de maatschappelijke kosten (*die zijn geïnventariseerd door de startanalyse van het PBL*)?
- Volgens experts van de netbeheerders zijn er geen technische belemmeringen bij de toepassing van waterstof in de bestaande bouw (geschikt gasnet, ketels beschikbaar, leveringszekerheid bij gelijkblijvende warmtevraag): wat zijn volgens uw uitdagingen bij de toepassing van waterstof?
  - Kunt u voor mij deze uitdagingen categoriseren? *Sociaal*, *economisch*, …
  - Wat zijn potentiële oplossingen voor deze uitdagingen?
- Wat zijn volgens u in **het algemeen** kansrijke buurten voor de toepassing van waterstof als energiedrager?
  - Zijn buurten het geschikte schaalniveau voor deze toepassing?
  - Wat zijn volgens u belangrijke argumenten/afwegingen bij het kiezen van het schaalniveau?

4. Afwegingskader

“We hebben zonet al gesproken over kansrijke buurten in het algemeen. In het volgende deel van dit interview wil ik graag verder het beoogde afwegingskader induiken. Tot nu toe doelde ik op een drietal criteria (technisch-ruimtelijk, bouwkundig en milieukundig). Op basis van de gesprekken die ik tot nu toe heb gevoerd, ben ik er echter van overtuigd dat een verbreding van de criteria handig oftewel noodzakelijk is.”

- Wat zijn volgens u relevante criteria die bij een degelijk afwegingskader van belang kunnen zijn, en die de prioritering op wijkniveau kan beïnvloeden?
    - Beschikbaarheid van waterstof
    - Verhouding tot andere duurzame alternatieven (in het kader van de warmtetransitiekaart)
- Welke afwegingen oftewel ruimtelijke argumenten zijn van belang bij de locatiekeuze?
    - Afstand tot nationale backbone (GasUnie)
    - Opwekmogelijkheden in de buurt (bijvoorbeeld op industrieterrein)
    - Uitvoerbaarheid: loskoppelen van bestaand net i.r.t. leveringszekerheid
    - Aantal aansluitingen in gebied
- Wat voor type gebouwen zijn het meest geschikt, oftewel komen gekeken naar andere alternatieven in aanmerking?
    - Oude binnensteden (geen ruimte in de ondergrond, overlast aanleg)
    - Monumentale (/oude) panden (complexe verduurzamingsvraag)
    - Diffuse bebouwing (hoge maatschappelijk kosten aanleg infra)
    - Diverse bebouwing (complexe verduurzamingsvraag)
- Welke milieukundige afwegingen kunnen van belang zijn bij het prioriteren van gebieden?
    - CO_2-reductie op basis van warmtevraag (huidig fossiel energieverbruik)
    - Luchtvervuiling door graafwerkzaamheden (aanleg warmtenet, verzwaring elektriciteitsnet en plaatsen van meterkastjes)
- Welke sociale aspecten komen bij de warmtetransitie oftewel de wijkenergieplannen (+ uitvoeringsplannen) kijken?
    - Draagvlak/maatschappelijke acceptatie energie-innovatie (**INDICATOR?!**)
    - Percentage woningvoorraad in corporatiebezit
    - Energiecorporatie aanwezig in gebied

4.3 Excursion journal

Due to privacy issues the excursion journal has been left out in the public friendly version of thesis research.

4.4 Overview survey questions

Masterscriptie 'Waterstof in de gebouwde omgeving'

Waterstof aan de b(e/u)urt?

Beste deelnemer,

Ten eerste wil ik u bedanken dat u de tijd wilt nemen om mij te helpen bij mijn onderzoek in het kader van mijn masterscriptie over 'waterstof in de gebouwde omgeving'. Het invullen van deze vragenlijst duurt **ongeveer 10 minuten**.

Het **doel van mijn onderzoek** is een **ruimtelijk afwegingskader te ontwikkelen** dat uitsluitsel geeft over '*in welke buurt de inzet van waterstof als energiedrager meer/minder geschikt is*'. Daarmee wil ik komen tot een **prioritering van buurten** (meest - minst geschikt) op basis van criteria, waar volgens de warmtetransitiekaart een warmtenet of all-electric geen geschikt duurzaam alternatief is voor aardgas.

Het **toewijzen van een weging per criterium** door jou als expert staat centraal in deze vragenlijst. Dit gebeurt door een paarsgewijze vergelijking van elk criterium. Hoe dit werkt wordt zometeen uitgelegd.

Ik wil u hier alvast wijzen op de laatste vraag van deze enquete die betrekking heeft tot de **potentiële deelname aan een focusgroep** om de uitkomsten uit deze vragenlijst samen te duiden.

Bij vragen over deze enquete of tijdens het invullen hiervan kunt u mij bereiken via: 06 24 38 85 48.

Jonas Vollbrandt

Q1: De uitkomsten uit deze vragenlijst worden uitsluitend gebruikt als input voor mijn masterscriptie.
Gaat u ermee akkoord dat uw antwoorden geanonimiseerd gebruikt worden voor het onderzoek?

a. Ja (1)
b. Nee, dan wordt u naar het einde van de vragenlijst geleid (2)

Bij een evaluatiemethode (multicriteria-analyse), die helpt om een rationele keuze te maken tussen alternatieven op basis van meer dan één onderscheidingscriterium, is het van belang om inzichtelijk te hebben vanuit welk perspectief de expert een weging geeft aan een bepaald criterium.
Om een beeld van u als stakeholder te hebben, gaan de eerste paar vragen over uw achtergrond en betrokkenheid met oog op het thema waterstof.

Q2: Bij wat voor type organisatie werkt u?

a. Netwerkbeheerder (1)
b. Gemeente (2)
c. Rijksdienst (3)
d. Onderzoeksinstituut (4)
e. Anders (5)

Q3: Wat is uw functie binnen de organisatie?

a. Open antwoord

Q4: Q11 Bij wat voor type waterstofproject bent u betrokken?
(Bijvoorbeeld: waterstofproefwijk of onderzoek naar de sociale aspecten van waterstof) U hoeft de naam/plaats van het project niet te benoemen.

a. Open antwoord

Het volgende blok heeft betrekking tot de evaluatiemethode, oftewel de multi-criteria analyse die ten grondslag ligt aan mijn afwegingskader. De bedoeling hier is dat u als expert een weging geeft aan elk criterium doormiddel van een **paarsgewijze vergelijking van elk criterium**.

Uit de gesprekken die ik de afgelopen weken gevoerd heb met u en uw collega's binnen de waterstofwereld zijn uiteindelijk **7 criteria** naar voren gekomen. (**Belangrijk om hier te vermelden:** In de ontwikkeling van mijn afwegingskader heb ik alleen die criteria meegenomen die door meer dan de helft van mijn interview-respondenten zijn genoemd oftewel gevalideerd.)

Criteria

De volgende criteria maken onderdeel uit van de paarsgewijze vergelijking:
(Voor alle criteria wordt het CBS-buurtniveau gehanteerd)

- **Uitvoerbaarheid van overstap** (De complexiteit van de omzetting van aardgas naar waterstof met zo min mogelijk knippen om de leveringszekerheid in het bestaande gasnet zo min mogelijk aan te tasten en de vermazing intact houden)

- **Afstand tot waterstof backbone** (De afstand in meters tussen de nationale backbone en één buurt)

- **Aantal monumenten** (Het aantal gebouwen met een monumentale status uit de categorie Rijksmomument, gemeentelijk momument of beschermd stadsgezicht)

- **Sociale acceptatie** (Het percentage van bewoners dat open staat voor de inzet van een innovatieve verwarmingstechniek zoals waterstof in plaats van aardgas)

- **Corporatief bezit** (Het percentage van de woningvoorraad in bezit van woningcorporaties)

- **CO2-besparing** (de hoeveelheid CO2 in kg die bespaard wordt door vervangen van aardgas door groene waterstof voor verwarming en elektriciteit voor koken op inductie)

- **Verduurzamingsopgave op grote schaal** (De complexiteit van een grootschalige verduurzaming op buurtniveau die beïnvloed wordt door de diversiteit aan gebouwtypologieën, verschillende gebruikersfunctie en aantal adressen per pand)

Uitleg evaluatiemethode

Criteria zijn niet altijd even belangrijk. Daarom is het nodig om voor elk criterium vast te stellen hoe belangrijk het is ten opzichte van de andere criteria.
De relevante criteria zijn georganiseerd in een matrix, waar de informatie in rijen en kolommen is geplaatst. In deze matrix heeft elk criterium een eigen rij en kolom. Hierdoor wordt de paarsgewijze vergelijking tussen alle criteria mogelijk gemaakt.

Om de vergelijking tussen de criteria te doen, wordt een **getallenschaal (1-9)** gebruikt die aangeeft **hoeveel belangrijker één criterium is dan een andere criterium.** Het gaat dus telkens om een vergelijking tussen **twee** criteria en **niet om het opstellen van een rangorde** van alle criteria.

Het getallenschaal is als volgt opgebouwd:
1: Even belangrijk
...
5: Sterk belangrijk
...
9: Extreem belangrijk

Belangrijk te vermelden: Het invullen van één 9 bij een vergelijking betekend **niet** dat het 9 keer zo belangrijk is. Bij deze **ordinale** schaal is de volgorde duidelijk, maar zijn de verschillen niet interpreteerbaar.

Omgekeerd getal: Als criterium x een van de bovengenoemde getallen toegewezen heeft gekregen bij een vergelijking met y, dan heeft y de omgekeerde waarde in vergelijk met x. Hieronder volgt een voorbeeld van een matrix.

(Voorbeeld)

Q5: Hoe beoordeeld u het belang van één criterium ten opzichte van een andere?
Uiteindelijk moeten alle vakjes ingevuld zijn!

	Uitvoer-baarheid van overstap	Afstand tot backbone	Aantal monu-menten	Sociale acceptatie	% corpo-ratief bezit	Hoeveel-heid Co2-besparing	Verduur-zaming op grote schaal
Uitvoerbaarheid van overstap	1						
Afstand tot backbone		1					
Aantal monumenten			1				
Sociale acceptatie				1			
% corporatief bezit					1		
Hoeveelheid Co2-besparing						1	
Verduurzaming op grote schaal							1

Om duiding en verdere diepgang aan de uitkomsten te geven, beoog ik **in het vervolg één of twee focusgroepen** te organiseren.
Een focusgroep is een kwalitatieve onderzoeksmethode waarbij een **groep experts wordt samengebracht om** over een vooraf bepaald onderwerp **te discussiëren**.

Tijdens mijn focusgroep(en) wil ik graag over de volgende onderwerpen discussiëren:
- **Uitkomsten van de criteria-weging** (Zijn er grote verschillen tussen de verschillende meningen van experts?)

- **Verdere ruimtelijke afbakening van de criteria** (bijvoorbeeld: wat wordt precies bedoeld met de afstand tot de backbone?)

- **Vaststellen van potentiële drempelwaarden** (bijvoorbeeld: wanneer is het aantal monumenten verwaarloosbaar?)

Q6: Staat u open voor deelname aan een focusgroep?
Indien u hiervoor open staat en 'ja' selecteert, volgt een vraag naar uw naam.

a. Ja (1)

b. Nee (2)

Q6b: Wat is uw naam? Aangezien ik uw mailadres al heb, kan ik vervolgens met u contact opnemen om de deelname aan de focusgroep verder te bespreken.

a. Open antwoord

4.5 Interview guide focus group

The interview guide includes: (a) overview of topics to be discussed, (b) statements regarding the spatial demarcation meant as food for thought for the experts, (c) quantitative data on various criteria to be discusses and (d) an example of the pairwise comparison.

Gespreksleidraad focus groep masterscriptie "Waterstof in de gebouwde omgeving"

Opgesteld door:	Jonas Vollbrandt (masterstudent sociale planologie)
Methode:	Focus groep
Gespreksduur:	90 – 120 minuten
Respondenten:	[redacted]

Onderzoeksobjectief

Het doel van dit onderzoek is het ontwikkelen van een ruimtelijk afwegingskader, dat uitsluitsel geeft over 'in welke buurt de toepassing van waterstof het meest geschikt is' (prioritering op buurtniveau). Hiervoor zijn in eerdere gesprekken relevante (ruimtelijke) criteria verzameld die een dergelijke afweging beïnvloeden. Daarnaast heeft een individuele weging van de criteria op basis van een paarsgewijze vergelijking plaatsgevonden.

Focusgroep doelstelling

De focusgroep is bedoeld om verdere diepgang aan de tot nu toe verzamelde uitkomsten (uit interview en vragenlijst) te geven. De doelstelling van de focusgroep is daarom **driedelig**:

- Ruimtelijke afbakening van de criteria (om deze gereed te maken voor een verdere analyse in GIS)
- Bepalen van potentiële drempelwaardes van criteria, en het potentiële categoriseren van waardes van criteria
- Paarsgewijze vergelijking van de criteria in groepsverband om te komen tot een 'definitieve' weging van de criteria

→ De gepresenteerde waardes (per criterium) zijn gebaseerd op data van de gemeente Groningen, gebruikt als voorbeeld in dit onderzoek.

1. Introductie en aanloop

- Welkom
- Toelichting onderzoeks- en focus groep doelstelling
- Toelichting vertrouwelijkheid, terugkoppeling op gespreksverslag en geaggregeerde rapportage
- Introductie respondenten (motivatie deelname focus groep)
- Korte reflectie op onderzoeksproces tot zo veer

2. Ruimtelijke afbakening criteria

→ *Hoe kunnen de criteria zo specifiek mogelijk gedefinieerd (omschrijving) en ruimtelijke afgebakend worden (ter voorbereiding op GIS-analyse)?*

- **Afstand** tot nationale waterstof backbone
  - Hemelsbreed: backbone – kadastrale grens buurt/middelpunt van buurt
  - Van GOS tot wijkdistributiestation
- Monumentale gebouwen (***aantal of percentage***), onderscheid maken in:
  - Rijks-/gemeentemonument
  - Beschermd stadsgezicht / beeldbepalend aanzicht
- Sociale acceptatie, alleen indirecte inschatting/benadering mogelijk door ***indicator***, op basis van verschillende sociaal-demografische factoren:

    - Inkomen
    - Leeftijd
    - Opleidingsniveau
- Complexiteit verduurzamingsopave op buurtniveau, ***indicator***, op basis van:
    - Aantal adressen per pand (= aantal belanghebbende)
    - Gebouwtypologieën (2-onder-1 kap, appartement, hoekwoning, tussenwoning, vrijstaand)
    - Bouwjaar
- **CO2-besparing** (bij 1-op-1 vervanging aardgas door waterstof), op basis van:
    - Huidig verbruik aardgas (in m3)
    - Verbruik in relatie tot aansluitingen?

→ Twee criteria zijn weggelaten in dit overzicht:
- Percentage woningvoorraad in corporatief bezit: is inherent ruimtelijke afgebakend
- Complexiteit van de overstap (CH4 → H2) op buurt niveau: Uit de interviews is gebleken dat de netwerkbeheerders hier zelf al een tijdje over puzzelen en dit specifieke onderwerp ook in werkpakket 7.2 (HyDelta 2.0) onderzocht wordt. Vanwege de complexiteit van dit vraagstuk heeft de onderzoeker besloten om dit buiten beschouwing te laten.

3. Drempelwaardes en categorieën (*onder voorbehoud van voldoende tijd*)
- Drempelwaardes voor criteria: (Wanneer) kan een criterium verwaarloosd worden?
    - Laagst/e aantal/percentage monumenten in buurt: 1x / afgerond 0%
    - Laagste percentage corporatief bezit: 3%
- Categorieën van waardes van criteria: (Wanneer) kunnen waardes van criteria samengevoegd worden, als bijvoorbeeld het onderscheid nihil is?
    - Afstand tot nationale waterstof backbone: Buurt A: 1250m – Buurt B: 1253m
    - Aantal monumenten: Buurt A: 21 – Buurt B: 22
    - Percentage corporatief bezit: Buurt A: 30% - Buurt B: 31%

    - Complexiteit verduurzamingsopgave:
        - Gemiddeld Bouwjaar (op basis van gangbare isolatiewaardes, zie bijlage B)
        - Aantal adressen per pand: Buurt A: 1 – Buurt B: 2
        - Gebouwtypologieën: dominant type gebouw vanaf % van?

4. Paarsgewijze vergelijking in groepsverband
- Uitleg methodiek
- Uitkomsten weging uit vragenlijst (zie bijlage C)
- Paarsgewijze vergelijk per criterium (zie bijlage D)

Vragen / stellingen

→ Deze stellingen hebben betrekking tot de ruimtelijke afbakening van de criteria

- Afstand tot nationale waterstof backbone: Wat wordt precies met de afstand tussen de nationale waterstof infrastructuur (van de Gasunie, beoogd realisatiedatum 2028) en een individuele buurt bedoelt?
    A. Kortste afstand hemelsbreed van toekomstige backbone tot middelpunt van CBS-buurt
    B. Kortste afstand hemelsbreed van toekomstige backbone tot gemeentelijke grens van CBS-buurt
    C. Kortste afstand tussen GOS (Gasunie) en districtstation (regionale netwerkbeheerder) langs bestaande gasleidingen

- Monumentale gebouwen:
    - Is het noodzakelijk om een onderscheid te maken tussen verschillende typen monumenten (gezien de voorwaardes voor verduurzaming)?
        A. Nee, geen onderscheid.
        B. Ja, een onderscheid omdat bij een gebouw met beschermd stadsgezicht het verduurzamen aan minder voorwaardes gebonden is.
    - Is het logischer de monumentalen gebouwen in aantallen of in percentage te beschouwen?

- Sociale acceptatie: Een exacte waarde kan een door een draagvlakmeeting bepaald worden. Voor een grove toetsing kan volgens onderzoek een indicator gebruikt worden. Wat is een logische verdeling (qua gewicht) voor deze indicator?
    A. Leeftijd: 50%?
    B. Inkomen: 25%?
    C. Opleidingsniveau: 25%?

- Complexiteit verduurzaming op grote schaal: Een exacte waarde voor dit criterium bestaat 'niet'. Hiervoor kan een indicator opgesteld worden, die gebruikt maakt van verschillende eigenschappen van de woningvoorraad. Wat is een logische verdeling (qua gewicht) voor deze indicator?
    A. Adressen per pand (aantal belanghebbende): 20%?
    B. Gemiddeld bouwjaar: 30%?
    C. Overheersende gebouwtypologie: 50%?

- Bouwjaar: Kunnen verschillende (gemiddelde) bouwjaren samengevoegd worden op basis van gangbare isolatiewaardes (zie bijlage B) om sneller te komen een overheersend bouwjaar?
    A. Alles voor 1920
    B. 1920 – 1965
    C. 1965 – 1975
    D. 1977 – 1988
    E. 1988 – 1992
    F. 1992 – 2012
    G. 2012 – 2018 (geen gasaansluiting meer voor nieuwbouw)

Bijlage

A. Spectrum waardes per criteria

Criterium	Minimum	Maximum
Monumentale gebouwen		
- Aantal	0	371 (=10%)
- Percentage	0%	25% (=6x)
Percentage corporatief bezit	0%	67%
Complexiteit verduurzamingsopgave		
- Adressen per pand	1	58
- Bouwjaar (gemid.)	1897	2019
Gebouwtypologieën		
- 2-onder-1 kap	0%	49%
- Appartement	0%	95%
- Hoekwoning	0%	29%
- Tussenwoning	0%	51%
- Vrijstaand huis	0%	100%
Verbruik CH4 (in m3)	1048m3	7027m3

B. Gangbare isolatiewaardes op basis van bouwjaar:

Bouwjaar	R_c-waarde vloer [m²K/W]	R_c-waarde gevel [m²K/W]	R_c-waarde dak [m²K/W]	Beglazing
< 1920*)	0,17	0,29	0,30	Enkel glas
1920 – 1965*)	0,17	0,43	0,30	Enkel glas
1965 – 1975*)	0,17	0,43	0,86	Enkel glas
1975 – 1988	0,52	1,30	1,30	Enkel glas
1988 – 1992	1,30	2,00	2,00	Dubbel glas**)
1992 – 2012	2,50	2,50	2,50	Dubbel glas
2012 – 2015	3,50	3,50	3,50	HR++
2015 – 2021	3,50	4,50	6,00	HR++
> 2021	3,70	4,70	6,30	HR++

*) isolatie was nog niet verplicht.

**) Alleen van toepassing voor woonkamers en keukens. Overige ruimten: enkel glas.

C. Uitkomsten paarsgewijze vergelijking

Criteria	Relatief gewicht	CR
Complexiteit overstap	12,4%	
Afstand tot nationale waterstof backbone	19,7%	
Monumentale gebouwen	7,1%	
Sociale acceptatie	40,7%	
Percentage corporatief bezit	4,1%	
CO2-reductie	7,8%	
Complexiteit van verduurzaming op grote schaal	8,2%	4,3%

→ Het percentage staat voor hoeveel % elk criterium de uiteindelijk beoordeling beïnvloed

C. Paarsgewijze vergelijking

→ Geef voor elke rij aan: hoe belangrijker is het criterium in de linker kolom t.o.v. het criterium in de rechter kolom met betrekking tot het einddoel: de beoordeling van de (hoge/lage) geschiktheid van buurten voor het gebruik van waterstof als energiedrager? Het gaat om het bepalen van een prioritering van buurten, die meer/minder geschikt zijn voor verwarming met waterstof.

→ In totaal wordt om **21 paarsgewijze vergelijkingen** gevraagd.

Belangrijk: Het gaat alleen om buurten waar (A) een **gasnet aanwezig** is & (B) volgens het warmtetransitieplan een warmtenet of all-electric oplossing **niet geschikt** is.

Criterium	**Schaal**									**Criterium**
Complexiteit van overstap	9	7	5	3	1	3	5	7	9	Afstand tot nationale backbone
Complexiteit van overstap	9	7	5	3	1	3	5	7	9	Monumentale gebouwen
Complexiteit van overstap	9	7	5	3	1	3	5	7	9	Sociale acceptatie
Complexiteit van overstap	9	7	5	3	1	3	5	7	9	Percentage corporatief bezit
Complexiteit van overstap	9	7	5	3	1	3	5	7	9	CO2-reductie
Complexiteit van overstap	9	7	5	3	1	3	5	7	9	Verduurzaming op grote schaal

Afstand tot nationale backbone	9	7	5	3	1	3	5	7	9	Monumentale gebouwen
Afstand tot nationale backbone	9	7	5	3	1	3	5	7	9	Sociale acceptatie
Afstand tot nationale backbone	9	7	5	3	1	3	5	7	9	Percentage corporatief bezit
Afstand tot nationale backbone	9	7	5	3	1	3	5	7	9	CO2-reductie
Afstand tot nationale backbone	9	7	5	3	1	3	5	7	9	Verduurzaming op grote schaal

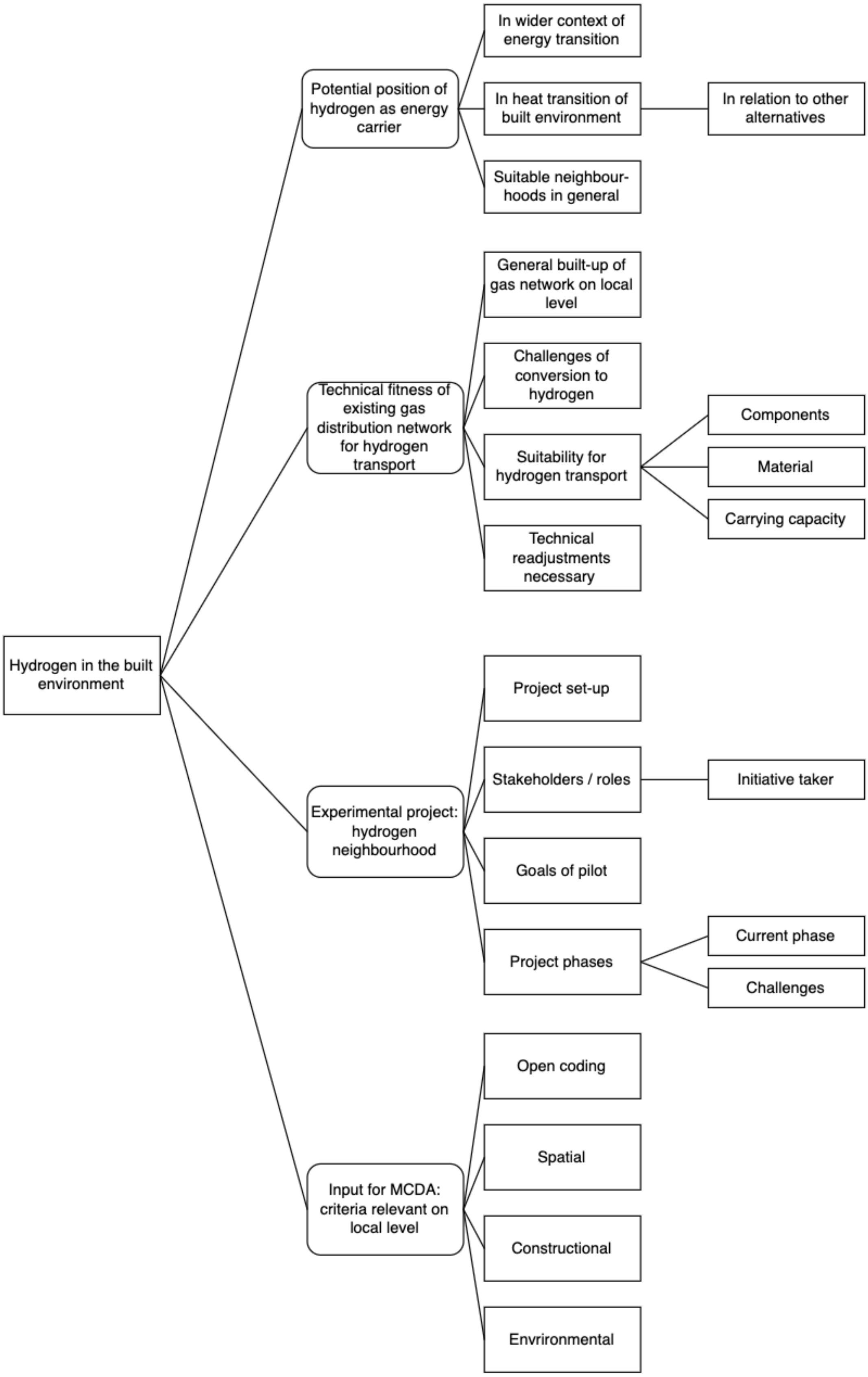
Monumentale gebouwen	9	7	5	3	1	3	5	7	9	Sociale acceptatie
Monumentale gebouwen	9	7	5	3	1	3	5	7	9	Percentage corporatief bezit
Monumentale gebouwen	9	7	5	3	1	3	5	7	9	CO2-reductie
Monumentale gebouwen	9	7	5	3	1	3	5	7	9	Verduurzaming op grote schaal

Sociale acceptatie	9	7	5	3	1	3	5	7	9	Percentage corporatief bezit
Sociale acceptatie	9	7	5	3	1	3	5	7	9	CO2-reductie
Sociale acceptatie	9	7	5	3	1	3	5	7	9	Verduurzaming op grote schaal

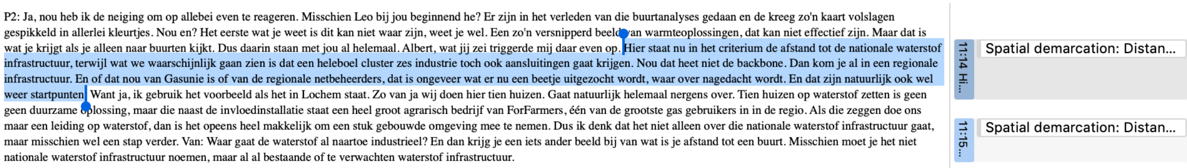
Percentage corporatief bezit	9	7	5	3	1	3	5	7	9	CO2-reductie
Percentage corporatief bezit	9	7	5	3	1	3	5	7	9	Verduurzaming op grote schaal

CO2-reductie	9	7	5	3	1	3	5	7	9	Verduurzaming op grote schaal

4.6 Coding tree semi-structured interviews

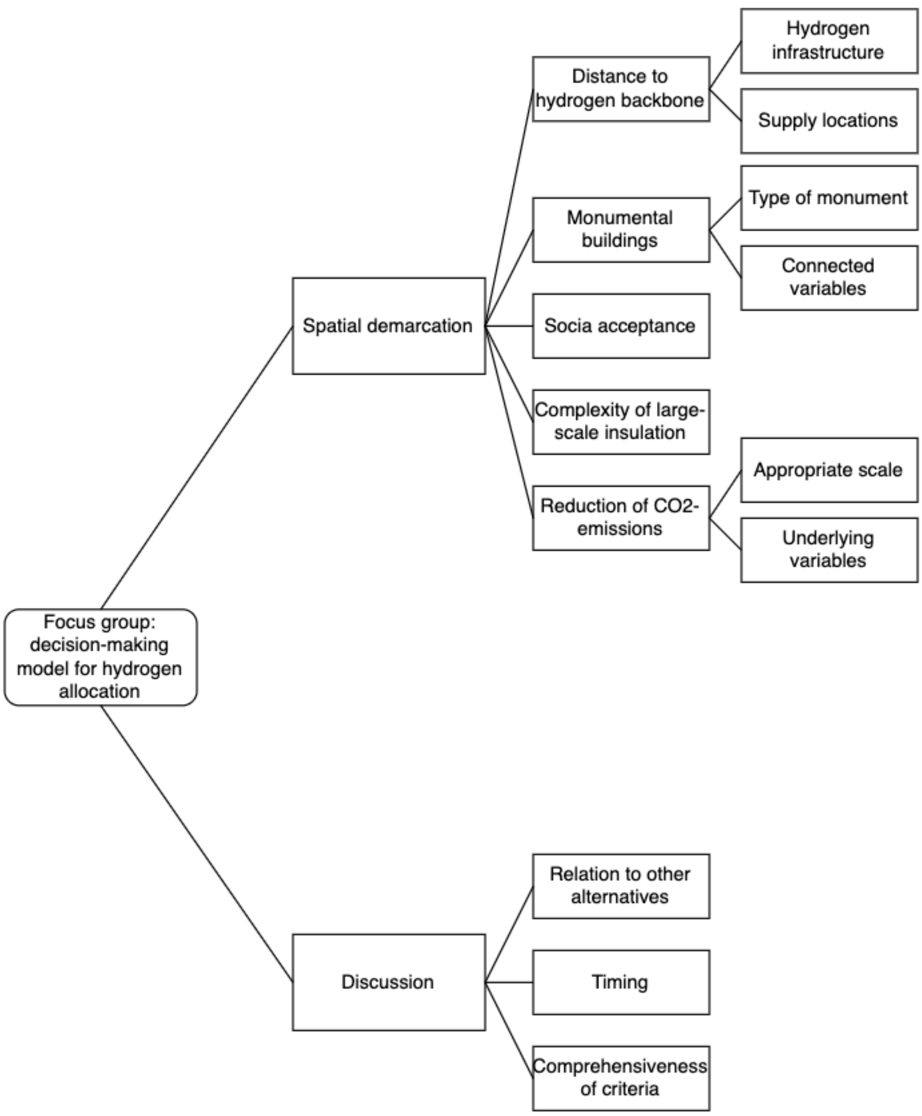


4.7 Example coding process interviews using ATLAS.ti


P2: Ja, nou heb ik de neiging om op allebei even te reageren. Misschien Leo bij jou beginnend he? Er zijn in het verleden van die buurtanalyses gedaan en de kreeg zo'n kaart volslagen gespikkeld in allerlei kleurtjes. Nou en? Het eerste wat je weet is dit kan niet waar zijn, weet je wel. Een zo'n versnipperd beeld van warmteoplossingen, dat kan niet effectief zijn. Maar dat is wat je krijgt als je alleen naar buurten kijkt. Dus daarin staan met jou al helemaal. Albert, wat jij zei triggerde mij daar even op. Hier staat nu in het criterium de afstand tot de nationale waterstof infrastructuur, terwijl wat we waarschijnlijk gaan zien is dat een heleboel cluster zes industrie toch ook aansluitingen gaat krijgen. Nou dat heet niet de backbone. Dan kom je al in een regionale infrastructuur. En of dat nou van Gasunie is of van de regionale netbeheerders, dat is ongeveer wat er nu een beetje uitgezocht wordt, waar over nagedacht wordt. En dat zijn natuurlijk ook wel weer startpunten. Want ja, ik gebruik het voorbeeld als het in Lochem staat. Zo van ja wij doen hier tien huizen. Gaat natuurlijk helemaal nergens over. Tien huizen op waterstof zetten is geen geen duurzame oplossing, maar die naast de invloedinstallatie staat een heel groot agrarisch bedrijf van ForFarmers, één van de grootste gas gebruikers in in de regio. Als die zeggen doe ons maar een leiding op waterstof, dan is het opeens heel makkelijk om een stuk gebouwde omgeving mee te nemen. Dus ik denk dat het niet alleen over die nationale waterstof infrastructuur gaat, maar misschien wel een stap verder. Van: Waar gaat de waterstof al naartoe industrieel? En dan krijg je een iets ander beeld bij van wat is je afstand tot een buurt. Misschien moet je het niet nationale waterstof infrastructuur noemen, maar al al bestaande of te verwachten waterstof infrastructuur.

The interview and focus group recordings and transcripts are available on request by sending an email to: Jonas.Vollbrandt@gmx.de.
Important note: an anonymized version of the transcripts will be sent, in order to safeguard the respondent’s privacy.

4.8 Coding tree focus group



4.9 Consensus matrix

Matrix ter beoordeling van consensus tussen deelnemers (leeg)

Vraag	********	*******	*******	********

A scan of the filled in consensus matrix during the focus group is available on request by sending an e-mail to Jonas.Vollbrandt@gmx.de.