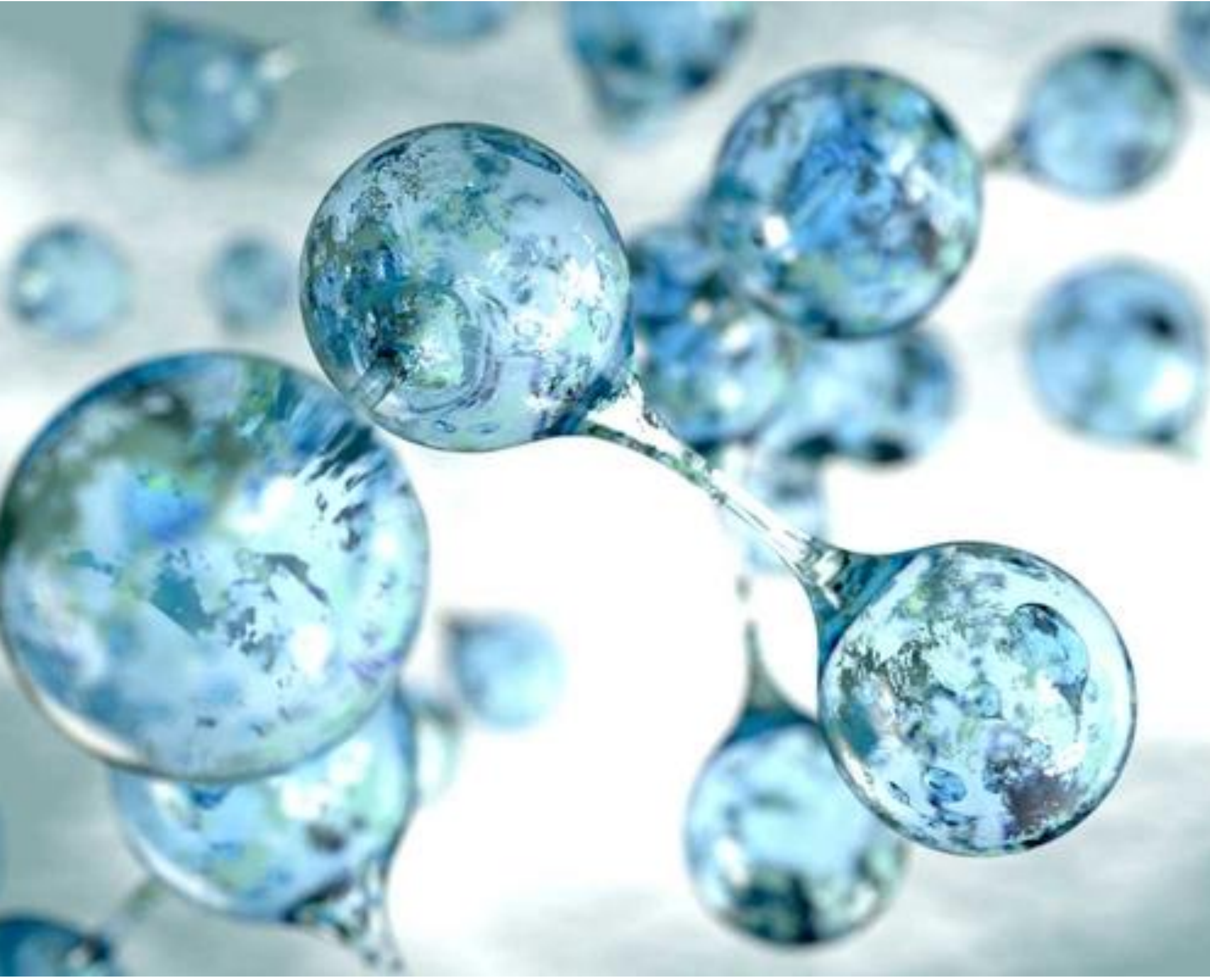

The trade-off between reliability and affordability of a hydrogen grid from the perspective of households

A stated choice experiment used to analyze preferences of households

Willemijn F.J. van Zijl

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Preface

In the past six months, I have worked on my thesis to complete the Master's program of Complex Systems Engineering and Management of the Delft University of Technology. The project was challenging, mainly due to the isolation we currently live in. When I searched for my graduation project, I never imagined that I would write the complete project from home. I would like to thank several people who helped me stay motivated and complete this project.

First of all, I want to thank my supervisors Rolf, Daniel, and Sander, for their feedback and guidance during my graduation project. Your critical feedback helped me to bring my thesis to a higher level.

Secondly, I would like to thank Stedin for allowing me to work on this new and innovative topic and to give me the opportunity to do my graduation project at their company. I would like to thank Frank for the guidance, time, and effort you took in helping me to complete this thesis. Moreover, I want to thank Tessa and Albert for the critical questions and reviews every two weeks.

Finally, I would like to thank my family for the moral support during the process and my entire study period in Delft. Also, I want to thank all my friends, study mates, roommates, and my boyfriend I made during my study period in Delft. My time in Delft would not have been so great without them. Thank you for all the conversations about the challenges I faced, the coffee and lunch breaks, and the distractions from my thesis. It helped me enormously to stay motivated and finish this project!

Willemijn F.J. van Zijl
Rotterdam, October 2020

Summary

In the last decades the trade-off between the reliability and affordability of the system used for heating is primarily determined based on the predefined level of reliability. In the current natural gas system almost no problems occurred due to this agreement. However, because of the development of sustainable energy the high level of reliability affects the affordability of the system. Hydrogen is seen as a sustainable resource that can fulfill part of the energy transition for the built environment. In the built environment the use of hydrogen with the predefined level of reliability leads to very high costs of the system. The reliability and affordability of the hydrogen system are of significant effect to the households that use the system and pay for it. Therefore, it is essential to investigate the preference of households related to the trade-off between a cost-effective and reliable network used for heating. In the heating domain the households' desired level of reliability at the associated cost and the households' possible preference for a less reliable network at lower costs are topics that remain uncovered. There is currently no understanding about the trade-off. Research can provide insight into the societal optimum between affordability and reliability and can foster the discussion about the design and regulations of a system used for heating in The Netherlands. Within this research the terms "(energy) consumers" or "public" refer to the households connected to the gas grid. The research question for this problem is: *"What are the preferences of Dutch households in the design of a reliable and affordable green hydrogen grid in the built environment?"*

Because energy systems are common-pool resources there is no one-on-one relationship between the investment cost of the grid operators (and energy companies) and the benefits of the households. While improved reliability of the energy system leads to higher investment cost, households must be willing to pay for the improved reliability of the energy system. The Willingness To Pay (WTP) is the maximum amount that consumers are willing to pay for a product or service. The WTP is a crucial factor when determining the price of products or, as in this research, the reliability. Reliability is "the ability to supply the quantity and quality of energy desired by the customer when it is needed" (McCarthly, et al., 2007, p.2153). A reliable natural gas infrastructure has continuous delivery without interruptions. The current reliability regulations state that grid operators are obliged to deliver gas to the households until an average temperature of -12 degrees Celsius. Figure 0.1 (Brown, et al., 1997) displays the relationship between the cost and the reliability of infrastructures. The right part of this figure shows that the cost will increase due to the improvements of reliability, caused by the fact that the last part of creating a 100% reliable infrastructure is costly, and high investment costs are necessairy (CPB, 2004).

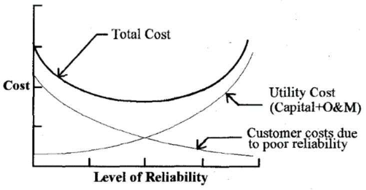

Figure 0.1 - [Reliability Cost Curves]. Retrieved from: Brown, et al., 1997. [Online Image]

Methodology

This research uses Discrete Choice Modeling to answer the research question. A stated choice experiment was conducted amongst households living in The Netherlands. The respondents needed to choose between six choice sets, consisting of four design variables. The design variables are the attributes found in literature related to the social, economic and technical characteristics of a hydrogen system. The cost reduction attribute defines the affordability of the system. The period with a maximum indoor temperature in a maximum number of rooms defines the reliability of the system.

In every choice set the respondent needed to choose between three alternatives: two sustainable hydrogen alternatives with a lower level of cost and reliability, and the current natural gas system. After the choice set a questionnaire was added to measure the socio-demographic and economic variables, the heating habits and housing characteristics, and the attitudes towards hydrogen. That the WTP for reliability was influenced by these variables and the preference for an alternative hydrogen design with a lower level of reliability were both a hypothesis in the research. The dataset contains the answers of 411 respondents. A panel mixed logit is used to in order to answer the research question.

Findings

On average, Dutch households prefer the design of a hydrogen system with a lower level of reliability over the current natural gas system. However, for the preference of an alternative hydrogen design over the current system, there is a significant level of unobserved heterogeneity that cannot be explained by the variables added to the model.

A system with a higher indoor temperature mostly influences the choice of households. Furthermore, households are sensitive to cost reductions and households prefer a system that can heat more rooms than just one. Overall, households dislike extended periods with constraints. The cost reduction and the indoor temperature are the most influencing factors in the choice for an alternative hydrogen design. Households are heterogeneous about the utility they obtain from different levels of the maximum indoor temperature, the number of rooms heated and the cost reduction. This research found no significant heterogeneity for the time constraint attribute. There is consensus about the dislike for the amount of time with a constraint.

This report identifies a gap between the average WTP for reliability and the current cost of the natural gas system. The identified gap can be stated with 95% certainty. The expectation is that a hydrogen system will be more expensive than the current natural gas system, especially in the beginning and during the transition phase. In the beginning, there are no infrastructure or generation facilities. The implementation of expensive hydrogen infrastructures on a local level will significantly increase the cost. The construction of an electrolyser serving demand until -7℃ instead of -12℃ can decrease the cost by 15%. The cost reduction caused by lowering the investment cost can decrease the gap between the WTP and the cost of heating. Cost reductions of 15% ensure that the gap between the WTP and the cost cannot be stated with 95% certainty anymore. If the current regulation forces the grid operators and the energy companies to implement a hydrogen system that meets the current reliability regulation, the gap between the WTP of households and the cost of heating will further increase instead of decrease.

The WTP for reliability is significantly influenced by the expectations that households have of the use of sustainable heating. Households that expect to use sustainable heating are willing to disconnect their house from the natural gas grid and use sustainable heating as an alternative. The gap between the WTP and the costs will further increase when the household has a higher expectation of using sustainable heating. Grid operators cannot force households to change their heating connections from natural gas to sustainable fuels. Furthermore, one can expect that always a certain percentage of inhabitants should be willing to change their heating connection before a sustainable system used for heating can be implemented. Therefore, the first neighbourhoods that shift from natural gas to hydrogen are doing so because they have opted for using sustainable heating.

The transition phase is expensive, especially if the system has to be very reliable from day one. The results imply that households willing to use sustainable heating prefer to reduce the reliability of the hydrogen system to ensure the system will not become too expensive. Therefore, considering to make the reliability regulations for the transition phase less strict than the reliability regulations for the final phase is crucial. The transition regulations can contribute to the development of an affordable, reliable, and sustainable hydrogen grid. Frontrunners seem willing to reduce their demand during peak hours, creating flexible demand in the coming years. Grid operators can make use of the demand to match supply and demand.

Discussion and conclusion

The main scientific contribution of this research is the assessment of the trade-off between the reliability and affordability of an energy system from the households' perspective. The analysis of this particular trade-off has never been the subject of discussion. The system used for heating has reliability regulations. The cost of the energy infrastructure is determined based on these reliability regulations. The reliability has never been weighted to the affordability goal, especially not from the households' perspective. This research provides insights into the preferences of the households in the trade-off between a reliable and affordable energy system. Moreover, this research quantifies the households' Willingness To Pay (WTP) for energy systems.

A higher level of reliability increases the cost (CPB, 2014; Brown, et al., 1997). The total cost line in Figure 2 shows this relation. This research shows that investments in the natural gas system are not economically efficient—the cost of reliability outreach the average WTP for reliability by the Dutch households. Households do not transfer the efforts taken to create a very reliable natural gas grid into benefits. The natural gas grid has no optimum between reliability and cost since the cost does not display the benefit. The relationship between the cost and reliability of the natural gas system is in the blue striped rectangle in Figure 0.2. The cost and level of reliability are higher than the optimum shown by the green line.

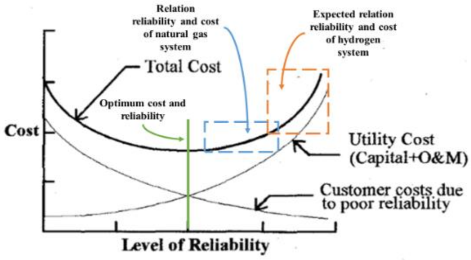

Figure 0.2 - [Reliability Cost Curves natural gas system and hydrogen system].

Implementing a hydrogen system will be more expensive than the current cost of the natural gas infrastructure. Especially the cost of reliability will increase. Therefore, the cost and reliability need to decrease in order to create an economically efficient hydrogen system. If the current reliability regulations are guaranteed, this research expects that the relationship between cost and reliability in a hydrogen system will be visualized by the orange striped square in Figure 0.2. The level of reliability needs to be reduced in order to create an optimum between cost and reliability.

Concluding, the government should reconsider the national reliability regulations and aim at creating regional reliability regulations for the transition phase. For the transition phase, it is crucial to look at conditions on a local level. In the coming years, local conditions should be used to determine the trade-off between reliability and affordability. Also, the hydrogen system does not necessarily have to be very reliable from day one. Transition regulations can help to start the hydrogen transition affordably.

Not only the generation capacity should be used to match supply and demand. Households can reduce their hydrogen demand during peak hours. Grid operators can incentivize households to reduce their demand or technical constraints can be added to the system in order to make sure that households do not use not too much hydrogen during peak hours. Moreover, in-house, advanced, conversion systems can be implemented to spread the demand. Finally, grid operators can restrict large consumers in their hydrogen demand. The hydrogen needs to become more affordable and less reliable from the perspective of the households. Grid operators, energy companies and the government should guarantee reliability in another way than they do today.

Also, several limitations of this research can be identified. The first shortcoming of this research is that no representative sample for the Dutch population filled in the survey. It is expected that because the sample is unrepresentative, the use of another sample might lead to different outcomes. Furthermore, self-selection may have occurred. Respondents were free to fill in the survey, which can imply that respondents with an opinion about the subject are more likely to fill in the survey. Another bias that is likely to occur in choice experiments is the hypothetical bias. The researcher is never sure whether the choices made in the survey are the same as in real life. There are no real consequences to the choices.

Furthermore, there is a significant amount of unobserved heterogeneity. The unobserved heterogeneity implies that the attributes do not explain all factors that households consider when choosing a system used for heating. Households likely consider more attributes when deciding for a system used for heating than those added in the stated choice experiment. Another limitation of this research is the presence of non-trading behavior. The drivers of non-traders differ, but it is almost impossible to recognize the drivers based on the data. Non-trading behavior can influence the parameter estimates and the WTP estimates.

Lastly, the period of the conduction of the research should be considered. The survey is distributed in summer and it is reasonable to assume that in summer respondents are more optimistic about reducing their gas use than in winter. Furthermore, it is essential to consider that due to the present COVID-19 crisis, households are more often at home. Therefore the households experience the downsides of a less reliable system more than when they are away from home a large part of the day. This may lead to too negative estimations of parameters compared to a non COVID-19 situation.

Recommendations

Stedin should start collaborating with other grid operators and, perhaps, energy companies and lobby for different reliability regulations. The government should relax the existing the national reliability regulations. This research suggests lobbying for a temperature -7°C in order to create an affordable and reliable system as desired by households. Furthermore, the grid operators should lobby for creating transition regulations that focus on the regional character of the transition and on the fact that the first neighbourhoods are frontrunners in the hydrogen system. Stedin should support the lobby by identifying different options to match supply and demand during shortages. They need to collaborate with energy companies and monitor the available supply of hydrogen.

Moreover, grid operators should consider the different options to ensure that they can lower demand during shortages. They need to identify large energy consumers and develop an inventory of their willingness to reduce their demand during shortages. Also, they should consider ways to incentivize households to reduce their demand and the question whether it is legally possible to create contracts for end-users needs to be addressed. Furthermore, the desirability of contracts must be investigated.

Further research must reveal the possibility of implementing technical constraints in the gas grid to reduce hydrogen distribution to houses. Also, the effect of advanced hydrogen conversion systems on the spreading of peak demand must be investigated. Furthermore, research must indicate to what extent the wishes of the households can be taken into account for the design of a future proof hydrogen system. The design is required to be stable and not very susceptible by the changing perceptions of households. Qualitative research can provide insights into ways to incorporating flexible demand and the preferences of households in the hydrogen design. Moreover, through qualitative research is can be determined what aspects of energy systems are essential to households. Also, research should determine ways to incorporate the demand for hydrogen in the reliability regulations.

The influence of generating more hydrogen on the capacity of sustainable electricity sources is left out of scope. One can expect that when more hydrogen capacity must be available, consequently more electricity capacity is needed and this leads to an even more expensive infrastructure. More research should reveal the exact influence. Finally, this research focusses on the incorporation of the preferences of households on the design of a hydrogen grid. Further research should indicate whether the same relations can be found in other heating sources, such as electricity and heating grids.

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List of Abbreviations

DCM	Discrete Choice Modeling
EFA	Explanatory Factor Analysis
LRS	Likelihood Ratio Statistic
LL	Log-Likelihood
MNL	Multinomial Logit
ML	Mixed Logit
RRM	Random Regret Minimization
RUM	Random Utility Maximization
RP	Revealed Preference
SP	Stated Preference
WTP	Willingness To Pay

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1. Introduction

1.1 Problem identification

One of the essential sustainable development goals of the United Nations is to ensure access to affordable, reliable, and sustainable energy (United Nations, 2015). In The Netherlands, the national Klimaatakkoord defines the sustainability goal. The Klimaatakkoord has the central goal of reducing greenhouse gas emissions by 49% in 2030 compared to 1990 (Klimaatakkoord, 2019, p.4). All sectors need to become sustainable to achieve this central goal. Different sustainability targets for these sectors are set. It is agreed that the built environment needs to reduce the CO_2 emissions by 2,4 Mton by 2030 and even become CO_2 neutral in 2050. Currently, most Dutch houses are heated by natural gas, which accounted for 13% of all the CO_2 emissions in 2018 (CBS, n.d.). Neighbourhoods must switch to different heating options such as a heating grid, all-electric heating, or heating using the sustainable gasses, hydrogen, or green gas to achieve sustainability goals. The optimal option differs per neighborhood (Klimaatakkoord, 2019, p.15-16).

The housing stock in the Netherlands contains around 7.5 million dwellings, from which more than 7 million dwellings are still connected to the natural gas grid (Visscher, 2019; Netbeheer Nederland, 2019a). Households are the occupants living in these dwellings and consist of one or more persons. The complete Dutch housing stock needs to be cut off from natural gas before 2050 to become CO_2 neutral. To accomplish this goal, by 2021, yearly 50.000 of the existing houses have to be made natural gas-free (Visscher, 2019). It is essential to start looking for opportunities to make the residential area sustainable.

Regional grid operators distribute gas (and electricity) to the residential areas in the Netherlands. Stedin is a regional grid operator in the Netherlands and is responsible for 2.2 million connections to the natural gas grid. The energy infrastructure has to change due to sustainability goals. The consequences of these changes on the distribution of energy are the capacity enlargement of the electricity grid, the removal of the natural gas grid to give way to other sustainable resources, or adjustments of the natural gas grid for using sustainable gases such as hydrogen (Stedin, 2017).

As a grid operator, Stedin is a frontrunner on the research and with pilot projects for the use of hydrogen as heating fuel. A primary advantage of hydrogen is that the current gas grid can be made suitable for transporting hydrogen relatively easily (Kiwa, 2018a). The investments already made in the natural gas grid can ensure an affordable energy transition, another crucial goal for the energy systems. The other identified goals of energy are reliability and affordability. Ensuring a reliable and affordable natural gas network is seen as an essential role of the grid operators (Stedin, 2017). Affordability and reliability are strongly connected.

Reliability concerns the quality of the network (CPB, 2004) and refers to the ability of the infrastructure to deliver the quantity and quality of energy as demanded by the users (ARENA, 2020). A reliable natural gas infrastructure has continuous delivery without interruptions. A downside of very reliable infrastructures is that it interferes with the affordability of infrastructures. Brown, et al. (1997) point out that very reliable systems cause higher capital and operational costs. It is generally accepted to state that the cost of a system is an increasing function of the reliability of the system. Each level of reliability comes with certain costs (Majety, et al., 1999). From an economic perspective, it is known that very reliable products come with high costs, while the consumer might opt for less reliable products with lower costs (Bahret, 2020). It is crucial to consider the reliability and affordability of energy systems simultaneously.

The energy system in the built environment will change to a more sustainable one. In the last decades, the reliability of the natural gas network is regulated by the Gaswet. The Gaswet states that the regional grid operators in the Netherlands are obliged to deliver gas to small consumers up to average temperatures of -12 ℃. This standard guarantees a high level of reliability since -12 ℃ is an extreme situation that almost never occurs in the Netherlands. The maintained grid and production capacity are based on the amount of gas used during this extreme period (Overheid, 2018; Overheid, 2016).

A problem identified by Stedin is that when the high-reliability level of a hydrogen infrastructure is guaranteed, the affordability of the infrastructure will decrease. The cost of electrolyzing is around 1000 – 1200 €/kW (TKI, 2019). The construction of an electrolyser that has high enough production capacity to meet the hydrogen demand during periods of low outside temperatures causes much higher investment cost compared to an electrolyser with less generation capacity. In the Netherlands, grid operators are not responsible for generating energy. Energy companies have to invest in and built these generating facilities. Grid operators are responsible for distributing enough energy to meet the reliability regulations and ensure a reliable and affordable natural gas network. Grid operators can predominantly influence the demand side of energy and collaborate with energy companies to achieve a reliable and affordable system. This collaboration is crucial in establishing a hydrogen system. The significant investment costs in electrolysers to meet the high level of reliability in a sustainable hydrogen system affect the affordability goal of Stedin.

Research has to be conducted to determine the preferred relationship between the reliability and the affordability of the system used for heating. It must be investigated whether the highly reliable and costly system, as opposed to a system with lower cost and a lower level of reliability, is preferable by the households. Research in this domain could give a start for the discussion about reducing the level of reliability and lower the cost of the energy infrastructure. A new optimum between the reliability and affordability has to be determined. Within this research, the term “(energy) consumers” or “public” refer to the households connected to the gas grid. This research will focus on the preferences of the households related to the trade-off between a reliable and cost-effective green hydrogen system used for heating. Eventually, it will contribute to the understanding and the assessment of the reliability and affordability of energy systems.

1.2 Knowledge gap

In the last decades, the trade-off between the reliability and the affordability of the system used for heating is primarily determined based on the predefined level of reliability. In the current natural gas system, hardly any problems occurred due to this agreement. However, caused by the development of sustainable energy, the high level of reliability affects the affordability of the system. Households are affected by the reliability and affordability of the system since they use and pay for the system. It is crucial to investigate the preference of the households related to the trade-off between a cost-effective and reliable network used for heating. The understanding of the relationship between reliability and affordability in systems used for heating is lacking. Research can give a different perspective about the societal optimum between affordability and reliability and can start the discussion about the design and regulations of a system used for heating in the Netherlands.

Literature from the electricity domain has proven that incorporating the preferences of households led to a different trade-off between the reliability and affordability of the electricity system. A few years ago, problems related to the reliability and affordability of the system occurred due to changing sustainability targets. The switch to sustainable electricity sources, such as solar and wind, caused an intermittent and variable electricity supply (Billimoria & Poudineh, 2019). Simultaneously, the electricity demand has grown substantially over the past years, and it is expected that it will keep growing in the future (Swalehe & Marunghri, 2018). The electricity companies had to expand their generation facilities to maintain reliability in the system. The generation facilities were expanded to meet high peak demand during times with a deficit of sun and wind, rather than the average demand during periods with sun and wind.

It became apparent that the reliability of the generation and transportation facilities could be reduced if economic incentives were given to the households to switch their electricity demand during peak hours. Households prefer a system with a lower level of reliability and comfort in exchange for a more affordable electricity system. The electricity system is different from the system used for heating since the natural gas use during peak hours (during low temperatures) cannot be transferred easily to periods with less demand. Everyone wants to maintain a warm house, especially during low outside temperatures. However, the knowledge obtained from the electricity domain shows the importance of incorporating the preferences of the households to the trade-off between reliability and affordable hydrogen system used for heating.

1.3 Research objective

This research contributes to the existing literature by examining the households' preferences related to a green hydrogen system used for heating. With the transition from natural gas to green hydrogen, new infrastructures need to be designed. When designing an infrastructure, a trade-off between the level of reliability and the associated costs needs to be made (CPB, 2004). Currently, the preferences of households are not incorporated in the trade-off between a cost-effective and reliable system used for heating, even though it is known that very reliable products come at very high costs. Research has to be conducted to determine if the households prefer the current level of reliability with the associated cost.

This research focuses on the average Willingness To Pay (WTP) for reliable energy services and the general view on the trade-off between reliability and affordability of the system used for heating. The Willingness To Pay (WTP) is the maximum amount consumers are willing to pay for a product or service. The WTP is a crucial factor when determining the price of products or, as in this research, the reliability. A general view of the design for a system is needed. Individual preferences about connecting to a system with a certain level of reliability will change when households move to other places. Therefore, no robust and flexible energy system can be created based on individual preference. The hydrogen infrastructure will be laid down for many years. Additionally, Stedin applies non-discriminatory services across all households connected to the service grid of Stedin. Consequently, everyone should have the same level of reliability, and all the costs have to be divided amongst the affiliates of the gas grid.

This research aims to create more understanding about the trade-off between the affordability and reliability of a hydrogen system used for heating from the perspective of the households. The results of the research can be input for the discussion about the design and regulations for a future proof hydrogen system. This research determines the average WTP for reliability and the households' preferences related to the cost and reliability of a hydrogen infrastructure. This research analyzes whether households desire the current level of reliability and cost. The outcomes will help create a broadly accepted infrastructure used for heating, reduce the risk of too high investments in generation capacity, and help to achieve the goal of Stedin to realize and maintain a reliable and affordable system used for heating. This research focusses on the households connected to the natural gas grid in the Netherlands. Therefore, the terms "public" and "energy consumers" in this research refer to the households connected to the natural gas grid.

In line with the research objective, the following research question is identified:

"What are the preferences of Dutch households in the design of a reliable and affordable green hydrogen grid in the built environment?"

1.3.1 Sub-questions

The following sub-questions are identified to help to answer the main research question:

1. *What characterizes the relationship between the cost and reliability of energy systems?*
2. *What are the most important technical options to create a design with a reduced level of reliability of a green hydrogen network used for heating?*
3. *What are the most valued attributes and the most important choices by the public for the design of a green hydrogen grid used for heating based on discrete choice modeling?*
4. *What explanatory factors significantly influence the choice of a hydrogen system with a different level of reliability?*
5. *To what extent equals the cost of reliability services in the current natural gas system the Willingness To Pay (WTP) of households?*

1.4 Academic and societal relevance

This master thesis contributes to the existing literature by identifying the preferences of the households related to the affordability and reliability of a green hydrogen grid used for heating within the built environment in the Netherlands. Since currently no research is conducted about whether households opt for a very reliable natural gas infrastructure, a future proof energy system is hard to design. Furthermore, factors that influence the choices of households are not yet known. Insights into the preferences of households are essential to design a new system. These insights can be used to optimize grid planning concerning the reliability and the cost of the network. New viewpoints from the households will broaden the understanding and the assessment of the reliability and affordability of energy systems. Within energy systems, the interaction with the households is a critical factor in determining the reliability and affordability and has to be considered in designing a green hydrogen infrastructure.

The fuel switch from natural gas to hydrogen will influence all the households that will be connected to a hydrogen grid. The outcomes of this research may influence the design of a hydrogen infrastructure used for heating. The trade-off between reliability and affordability in the hydrogen system might get differently weighted. The reliability of the system may be guaranteed more affordably.

The research is in line with the CoSEM master program since it explores innovation in a complex socio-technical environment. In this case, green hydrogen is the innovation that will be implemented in the built environment in the Netherlands. The socio-technical design is considered to create a preferred heating system that uses the contours of the existing regulation and distribution infrastructure as a starting point.

1.5 Research scope

This master thesis focusses on the Netherlands. The report only focusses on hydrogen as sustainable heating fuel. KIWA (2018a) showed that the current natural gas grid could be made suitable for using sustainable hydrogen relatively easily. Therefore, hydrogen is a suitable alternative for natural gas used for heating in the built environment in The Netherlands. Sustainable hydrogen will mainly be used in neighbourhoods that are difficult to heat by other options. The other heating techniques, such as all-electric, heating grids, and green gas, are not incorporated within this research. However, this research can be a starting point for incorporating the perspective of the household of these heating options as well.

This research will not focus on the actual production of green hydrogen. The green hydrogen comes from sustainable electricity sources, but neither the complete production process of green hydrogen nor where the green electricity comes from will be researched in this thesis. Also, the use of hydrogen storage facilities to reduce the generation capacity is not incorporated in this research. Stedin concludes that the use of local storage facilities probably exceeds the cost of constructing more generation capacity. The report of Berenschot (2019) supports the high cost for local storage. The high storage costs are caused by the necessity of high pressure to store hydrogen, and the storage facilities must store hydrogen for a very long period. The hydrogen is stored only for periods with extremely low temperatures. Therefore, this research does not further look into the possibility of storing hydrogen on a local level.

There are three forms of hydrogen that differ from the way it is produced. This research only focuses on sustainable hydrogen. The primary focus is on green hydrogen, produced from the conversion of green electricity in electrolysers. Blue hydrogen is also a form of sustainable hydrogen. Blue hydrogen is probably the stepping stone in the roll-out of the hydrogen infrastructure and is a sustainable form of hydrogen (DNV GL, 2020). Therefore, this research not defines the difference between blue and green hydrogen to households. However, since the production of blue hydrogen follows a different path than the production of green hydrogen, the production and investment cost will differ. This research mainly focusses on the production and usage of green hydrogen. Section 3.1 explains the different forms of hydrogen and the way of production.

1.6 Research design

This section discusses the different steps taken to answer the different sub-questions and the main research question defined in section 1.3. First, section 1.6.1 discusses the research approach. Section 1.6.2. elaborates on the analytical framework of this research. Finally, sub-section 1.6.3 defines the methods used per step to answer the research question.

1.6.1 Research approach

This research analyzes the preferences of the households related to the trade-off between a reliable and affordable hydrogen system. The report analyzes the trade-off by determining the households' Willingness To Pay (WTP) of the reliability services of a system used for heating. The WTP estimates are compared to the cost of the current gas network, after which conclusions for the design of a future hydrogen system are made.

This section presents the different stages needed to answer the main research question and the different sub-questions. Figure 1.1 shows a visualization of these stages in a research flow diagram.

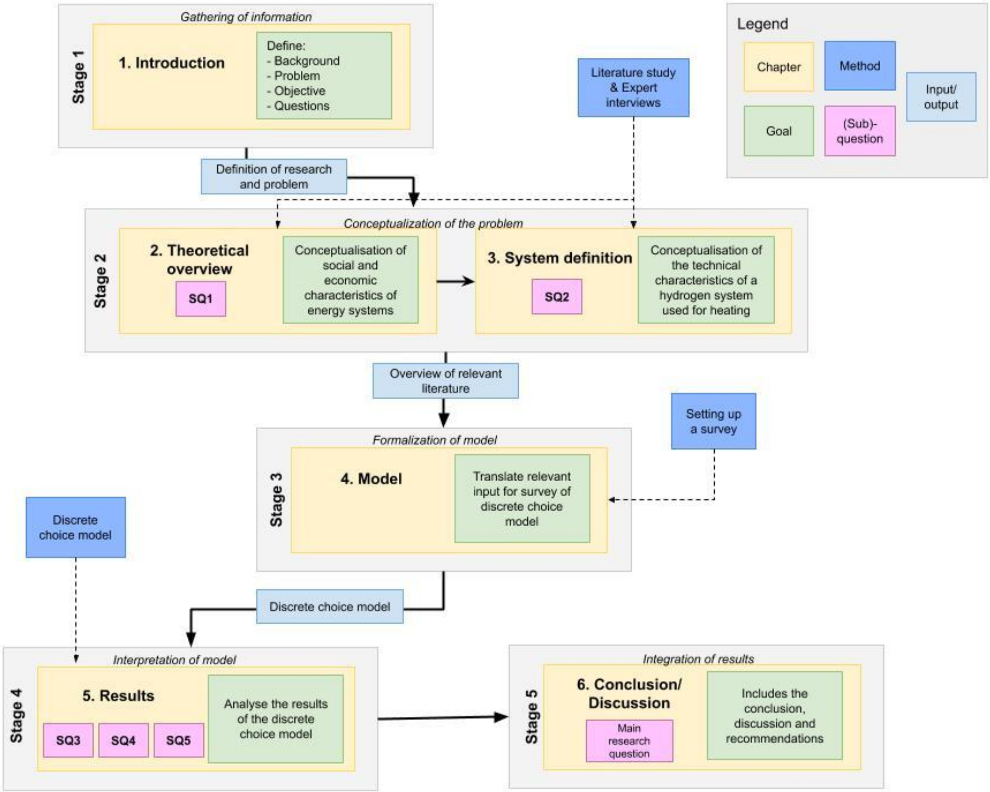

Figure 1.1 - Research Flow Diagram

The first stage gives an introduction to the problem (see chapter 1). The first part of the second stage focusses on the social and economic characteristics of energy systems. This part will consider energy systems as common-pool resources since this has implications on the trade-off between reliability and affordability. The essential characteristics and problems of common-pool resources are discussed. Furthermore, the relationship between the cost and reliability in energy systems is explained and specified for the current natural gas system. The chapter also elaborates on ways create a reliable system by stimulating households to use less hydrogen. Finally, factors based on literature are discussed that probably influence the households' WTP for the reliability of the system used for heating. This part answers the first sub-question.

Another part of this stage consists of analyzing the technical characteristics of the hydrogen system with a reduced level of reliability. This part first analyzes the investment, production, and transportation cost of hydrogen of different reliability levels. After that, the usage of hydrogen in the built environment is discussed. Also, technical requirements to incorporate adjustments in the demand in the hydrogen design are analyzed. This section will answer the second sub-question.

This report uses discrete choice modeling (DCM) to determine whether and to what extent households are willing to trade-off the cost and the reliability of the system used for heating. This thesis uses DCM due to several reasons, from which two are given here. First, DCM can quantify the values of the respondents given the different attributes and can determine the preferences of respondents for different attributes. Second, in DCM the respondents are asked for choices and not directly for their trade-offs. In this research, this way of asking will create benefits since judgment is more liable to bias than choices. Moreover, generally, people do not know their real trade-off if you ask them directly (Chorus, 2018). In this stage also the stated choice experiment will be set up. The insights gathered from the second stage will be the primary input of the discrete choice model. The most relevant attributes, together with different attribute levels, will be identified and structured.

After defining the stated choice experiment and the conduction of the surveys, the choices of the public related to the alternative hydrogen design can be analyzed. These findings will give insights into the preferences of the households related to the cost and the reliability of a hydrogen grid used for heating. This section also searches for the influence of explanatory factors on the preference of households. Finally, the households' WTP for reliability is determined and compared to the cost of reliability services. This stage answers the third, fourth, and fifth sub-question.

The final stage uses the insights of all previous stages. It concludes about the influence of the households' preferences on the trade-off between reliability and affordability in a hydrogen system. This stage answers the main research question. Furthermore, the findings are discussed based on the social and scientific contribution. Additionally, specific recommendations for Stedin are given.

1.6.2 Analytical framework

One can state that households want to have reliable infrastructures at a low cost. Reliability concerns the quality of the network (CPB, 2004) and refers to the ability of the infrastructure to deliver the quantity and quality of energy as demanded by the users (ARENA, 2020). The cost of a system is an increasing function of the reliability of the system. Very reliable products come with high costs (Brown, et al., 1997). Therefore, the reliability interferes with the affordability of infrastructures.

In a reliable energy system, there is always a match between supply and demand. The regulations force energy companies and grid operators to match supply and demand in a supply oriented way. In the heating domain, this is currently not seen as a problem, due to the gas field in Groningen, the storage facilities and the national natural gas grid. When introducing a hydrogen system, the cost of reliability will increase if the regulations hold/ Large generation facilities must be constructed since there is no national grid that can minimize shortages on a local level, and Stedin expects that in most cases, the cost of local storage facilities exceeds the cost of extra generation capacity.

A hydrogen system can be described as a common-pool resource. Stedin cannot exclude households from the distribution of hydrogen, and the consumption of hydrogen is rival (Künneke & Finger, 2009; Ostrom, et al., 1999). The cost of investment in the reliability of energy systems should be economically efficient and not outreach the benefits and the Willingness To Pay (WTP) of the households (Gill, et al., 2017). The Willingness To Pay (WTP) is the maximum amount households are willing to pay for a product or service. The WTP is a crucial factor when determining the price the reliability.

The cost of the hydrogen system must be in equilibrium with the benefits of the households obtained from the system. Therefore, the cost of the system must not exceed the WTP of households (Gill, et al., 2017). The cost of reliability must be compared to the WTP for reliability. Comparing the WTP and the cost of the reliability of the natural gas grid gives insight for the design of a hydrogen system. A gap between the WTP and the cost implies that the current system is already too expensive, and the trade-off between affordability and reliability must be made differently. Moreover, it raises the idea of considering the incorporation of flexible demand to match supply and demand.

1.6.3 Methods used per stage to answer the research question

This thesis uses a modeling approach to look at the preferences of the households related to the design of a cost-effective and reliable hydrogen system used for heating. The modeling approach helps to create insights into the preferences of the households. A major advantage of a modeling approach is that scientific models can help to predict the future. It helps to understand processes that otherwise cannot and will not be realized in the real world. A more substantial scientific knowledge can be developed (Murmson, 2017). One must keep in mind that a model simplifies the real world, and it will not predict the exact future (Murmson, 2017).

This report identified different sub-questions (see section 1.3.1) to answer the main research question. Different methods will be used to answer the sub-questions. This subsection will discuss the different methods used to answer these sub-questions.

First, to answer the first and the second sub-question, a literature study is performed. First, the social and economic characteristics of energy systems are analyzed. After that, the technical characteristics of the hydrogen system with a reduced level of reliability are discussed. The outcome of the literature study will be input for the stated choice experiment. Additionally, the literature analyzes the Willingness To Pay (WTP) for reliability and the cost of reliability.

The third stage will treat the design of the Discrete Choice Model (DCM) and the stated preference experiment. For the construction of the stated choice experiment, the conclusions of the first and second sub-question will be used. The stated choice experiment will be set up by the use of Ngene, a tool to set up the attributes together with the different attribute levels.

The fourth stage will analyze the preferences of the households related to the cost and reliability of a hydrogen system. In the choice experiment, households will choose between different options, all with a different combination in value for the cost and the level of reliability. DCM is used to explain and predict the choice of the respondent from a set of three alternatives. DCM used assumes that the respondent will choose the alternative that maximizes his/her benefit or utility. DCM will help to determine the average WTP for reliability and to what extent the households prefer to reduce the level of reliability due to the increase in affordability (Colombia University, 2019; Horowitz, et al. 1994).

This thesis conducts the stated choice experiment by surveys among households within the Netherlands. The surveys are distributed by the customer panel and online channels of Stedin. Respondents for the stated choice experiment and data for the literature study are intended to be found by utilizing the network of Stedin and the TU Delft.

The fourth stage uses the software tool Python Biogeme to answer the third, fourth, and fifth sub-questions. This python package is specifically designed to estimate the parameters of Discrete Choice Models. The package identifies the value and relation between the attributes based on the choices of the respondents. The preferences of households of the reliability and affordability of systems used for heating are identified. Moreover, the influence of other variables, such as socio-demographic variables, heating habits, or attitudes on the preference of the households, is analyzed.

Finally, the last stage answers the main research questions, discuss the outcomes as well as the methods, and gives recommendations for the design of a hydrogen system to Stedin. This stage includes if the households desire the current design and regulations of the gas system. Also, possible implications for the design of a hydrogen system are discussed. Furthermore, this stage considers whether the incorporation of the preferences of the households can change the design of the sustainable hydrogen system. This stage returns to the literature study and the model outcomes of the previous stages.

Figure 1.1 shows the visualization of the different stages and their relations. It visualizes that the output of the previous stages is the input for the next stage.

2. Social and economic characteristics of energy systems

This section describes the existing state of the art literature about the social and economic characteristics of energy systems. The chapter starts with the characterization of energy systems as common-pool resources. This identification will elaborate on the relationship between the investment costs made by the grid operators and the benefits obtained from these investments by the households. It will give a better view of the costs made in the gas network and the relation between the costs and the usage of the system. After that, the chapter elaborates on the relationship between the terms cost and reliability. Subsection three focusses on the reduction of reliability on the supply side by using the demand. The fourth subsection looks into different factors that influence the Willingness To Pay (WTP) of the households for a reliable energy system. The end of this chapter answers the first sub-question.

This research aims to discover the preferences of households related to a reliable and affordable heating system by the use of Discrete Choice Modeling. This chapter partially defines the attribute input of the survey design in Chapter 5.

2.1 Energy network as a common pool resource

Energy infrastructures are characterized as large man-made socio-technical systems. The possibility of exclusion of households from energy infrastructures is low. When looking particularly at the natural gas infrastructure, the transportation of natural gas is an essential service, and the distribution is politically motivated. Households cannot be excluded from the distribution of natural gas or hydrogen. Furthermore, the consumption of energy, such as natural gas or hydrogen, is rival, especially during scarcity. One individual cannot use the natural gas used by another individual. The energy system is an open access service in which the benefit of one individual is of the expense of the other individuals (Künneke & Finger, 2009; Ostrom, et al., 1999). Subsequently, it can be stated that energy systems, such as the natural gas system, are common-pool resources.

It is important to note that the amount of (natural) gas used by individuals can be monitored in cubic meters. However, the costs needed for transportation, extraction, or production of (natural) gasses cannot be individually monitored or divided (Künneke & Finger, 2009). These costs are needed to provide the service of gas delivery and usage. The gas system has several purposes that serve the need of individual consumption. The different purposes cause different needs for system developments and investments (Künneke & Finger, 2009).

A frequently addressed consequence of common-pool resources is called the "tragedy of the commons." This term relates to the situation in which the rational interests of individuals lead to major disadvantages for the public. A commonly used example is the extension of fish species due to overfishing (Goldthau, 2014). The challenge of overcoming the tragedy of the commons with common-pool resources is centered around access regulation and the creation of a fair distribution of the cost and benefits across the users (Ostrom, et al., 1999).

In the field of common-pool resources, the households must directly translate the efforts taken for reliable energy services into actual benefits. The households' benefits are related to the WTP for a reliable energy system (Gill, et al., 2017). The WTP for products the change in utility (benefit) of an individual by a consumption choice. A higher utility or benefit derived from service results in a higher WTP (Gill, et al., 2017). The WTP for a more reliable energy service decreases when the utility of the user will no longer increase due to better services.

The cost of investment for increasing the reliability of energy systems should be economically efficient and not outreach the benefits and the WTP of the households. The grid operators such as Stedin are responsible for the investments in the gas network. The gas grid can is a common pool resource, which causes that there is no one on one relationship between the investment cost of the grid operators and the benefits of the households. It is crucial to consider the benefits and the WTP of households to determine the investments needed in the gas network. Improved reliability of the energy system leads to higher investment costs, and the households should be willing to pay for the improved reliability of the energy system at higher costs (Hubana & Ljevo, 2019). The cost and reliability of energy systems are strongly related. The next section explains this relationship.

2.2 Trade-off cost and reliability

The goal of this research is to determine the trade-off between the reliability and affordability of energy services by households. This section comments on the economic environment of energy systems. First, the relationship between reliability and cost of energy systems is elaborated. After that, this relationship is specified for the natural gas system.

2.2.1 Reliability and cost of energy infrastructures

McCarthy, et al. (2007) defines the reliability of energy systems in terms of adequacy and security. The adequacy statically considers the system. It looks at the ability to supply the requirements of the customer under normal operating conditions. The security of the system defines the ability to endure unexpected interruptions and include the dynamic response of the system. The adequacy and the security of the system result in the reliability of the system. The reliability can is “the ability to supply the quantity and quality of energy desired by the customer when it is needed” (McCarthy et al. 2007). To put it differently, the reliability of a system “reflects the ability of the system to deliver the product (or service) transported over the network without interruption and deterioration of its quality” (CPB, 2004). Reliability is the “ability to maintain and execute error-free operations” (Shrivastava, et al., 2009).

The concept of reliability is strongly related to the term security of supply. However, both terms have different definitions. The term reliability concerns the quality of the network (CPB, 2004). Reliability refers to the ability of the infrastructure to deliver the quantity and quality of energy as demanded by the users (ARENA, 2020). The term security of supply is a more general term and concerns the provision of services and goods in the long term. Security of supply considers potential extreme disruptions on the supply side, such as an unexpected economic crisis that causes a sharp decrease in demand, or generators that break down (CPB, 2004). The security of supply of an energy system is the ability to remain stable and respond during these unexpected events. It is the technical resilience of the energy system (ARENA, 2020). This research will look at the reliability of energy systems and considers the ability of the energy system to meet the households’ demand.

CPB (2004) states that a decrease in the reliability of a system does not always reduce social welfare. It might even improve social welfare if the reliability level is above the appropriate level of reliability. The cost to create the level of reliability in the system is considered to be too high. When one includes the cost of the reliability of a network, this usually implies that a network is not 100% reliable. Systems are never entirely reliable. 100% reliability in networks is mostly seen as over reliable or too reliable. In an appropriate reliable system, the marginal social cost equals the marginal social benefits (CPB, 2004).

With infrastructures, the balance between cost and reliability is more challenging to obtain than by private goods. If the reliability of private goods increase, the cost will increase. The reliability increases until the cost leads to product prices that are not desired by the customers. The customers will not buy such products. A balance between reliability and cost should be obtained to sell private goods. (Bahret, 2020).

When considering energy systems, the indices used for reliability indicate the households' expectations of energy delivery. These indices focus on energy interruption frequency and duration and do not address the cost (Brown, et al. 1997). When searching for a system with low costs, it should be ensured that a system design does not lead to a massive decrease in reliability. Interruptions in energy systems need to be prevented and should be set as constraints of the system (Brown, et al. 1997). However, in an optimal design that meets the preferences of households, both reliability and cost should be considered. The households should be willing to pay for the investments of a reliable energy systems.

Figure 2.1 (Brown, et al., 1997) displays the relationship between the cost and the reliability of infrastructures. At first, the cost decrease with an increasing level of reliability, caused by less maintenance and service issues when the level of reliability increases (Brown, et al. 1997). In the right part of the graph, the cost will increase due to the improvements of reliability, caused by the fact that the last part of creating a 100% reliable infrastructure is costly, and many investment costs are needed (CPB, 2004).

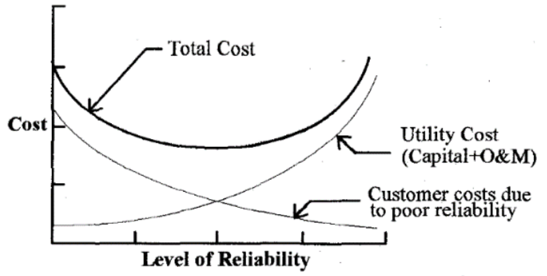

Figure 2.1 - [Reliability Cost Curves]. Retrieved from: Brown, et al., 1997. [Online Image]

2.2.2 Reliability and cost of the natural gas infrastructure

The Netherlands has one of the most secure and reliable natural gas networks globally (KIWA, 2018b). In the past five years, the households experienced, on average, 1 minute and 40 seconds without natural gas. Even in the countries surrounding the Netherlands, the natural gas disruptions take around two to three times longer (Netbeheer Nederland, 2020). In the Netherlands, a difference between the national and the regional grid operator exists. There is only one national grid operator, while there are several regional grid operators. The national grid operator is Gasunie Transport Services (GTS) (GTS, n.d.). Natural gas is transported from central points in the Netherlands or the international borders to the distribution grids. The national grid operator is responsible for the balancing of the gas grid. Balancing means the match between supply and demand.

In the future, the production of hydrogen will start at a more local and regional level (Gigler, et al., 2019). Therefore, hydrogen will enter the gas infrastructure in different local places. It becomes crucial to balance the grid on a local or regional level, instead of only on the national level. Regional grid operators are responsible for the local and regional distribution channels. It is reasonable to assume that grid operators will become responsible for balancing the regional and local distribution grid (Groenhuije, et al., 2003). To balance the grid, grid operators should collaborate with the companies that built the generation facilities of green hydrogen.

The regional grid operators manage the distribution grids. Based on the Gaswet, the regional grid operators are obliged to have an operational gas grid that they keep maintaining and developing to ensure the security and reliability of the grid (Groenhuijse, et al., 2003). The regional grid operators are bound to a specific region and are responsible for the construction and maintenance of the gas grid within this region. Regional grid operators are responsible for the transportation of gas to the end consumers until a temperature of -12°C (NEDU, 2020; Koppenol, 2016). To ensure the high reliability of the natural gas grid, the regional grid operators invest yearly around 800 - 900 million euros for the repairments, replacements, and expansion of the grid (Netbeheer Nederland, 2020).

There is no direct competition between the grid operators. Therefore, the grid operators are supervised by the Autoriteit Consument & Markt (ACM). Grid operators have information obligations towards the

ACM. Once every two years, the grid operators need to give the AMC a Quality- and Capacity document (Kwaliteits- en Capaciteitsdocument, KCD). In this document, the grid operators report about their quality performance and the capacity of their grids (Netbeheer Nederland, 2020). Based on the KCD, the ACM verifies whether the regional grid operators have sufficient grid capacity to guarantee transportation (Groenhuijse, et al., 2003).

The reliability of the natural gas grid is determined by the extent to which customers can rely upon the transportation of gas. The reliability of the natural gas grid is influenced by different factors such as interruptions, which negatively influence reliability and standards designed for the security of the grid, which increases the reliability of the grid (Groenhuijse, et al., 2003). Different quality indicators quantify the reliability of the Dutch distribution gas network. A low value of these quality indicators means high reliability of the grid. The quality indicators are average interruption time, the interruption frequency, the annual interruption time, and the average time to secure if a risky situation occurs (Netbeheer Nederland, 2018). The regional grid operators must keep these quality indicators low and also maintain a reliable grid. The ACM controls these indicators, and regional grid operators have to meet the quality standards. The grid operators must ensure that the quality standards remain low.

The regional grid operators are responsible for maintaining a reliable grid. The national grid operator must continuously balance the available grid capacity and the expected gas demand. It is expected that regional grid operators will also get this responsibility in the future (Stedin, 2018a). Next to the insurance of the reliability of the distribution grid, grid operators should make sure that the transportation of natural gas is affordable. Interestingly, the grid operators are obliged to have the defined grid capacity to ensure reliable transportation, also if this is very expensive. The cost made by grid operators for investments or maintenance of the gas grid is divided among everyone connected to the natural gas grid. In addition to that, the costs are equally divided among households (Netbeheer Nederland, 2019a). The cost to create a reliable grid is eventually paid for by households. Obtaining a reliable natural gas grid seems more important than the cost to obtain this level of reliability and whether the households are willing to pay for these costs.

2.3 Usage of demand to create a reliable gas system

On average, households use 79% of the domestic gas for space heating, while households use 19% of the gas to heat domestic water. Most domestic water is heated for showering (Bleekhuis, 2017). Cooking represents 2% of domestic gas use (Klip, 2017). Since 2% of the gas used for cooking is almost neglectable compared to the amount of gas used for space heating and domestic water heating, this research neglect the gas used for cooking. Moreover, hydrogen flames are invisible, through which it will be unattractive to cook with hydrogen (KIWA, 2018b).

The main purpose of the natural gas used in the residential sector is space heating. Consequently, natural gas use is strongly related to the outside temperature. During winter, a lot more gas is used than during summer (EBN, 2019). During summer, the average outside temperature is 17,0°C (KNMI, 2019b), while the average temperature during winter is 3,4°C (KNMI, 2019a). During summer, the houses are generally heated by the outside temperature, and the natural gas use is low. During winter, gas is needed to heat the houses. During freezing winters, more energy, so more gas is needed to heat the houses. Figure 2.2 displays the average gas use in the Netherlands.

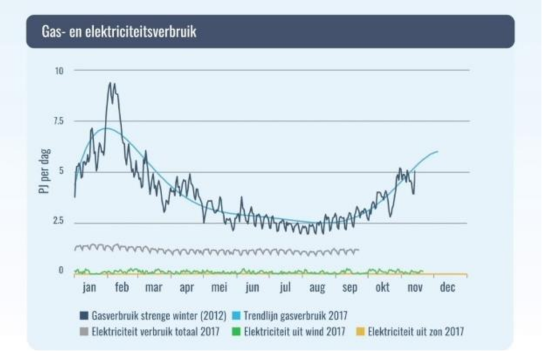

Figure 2.2: [Gas demand The Netherlands]. Retrieved from: EBN (2019). ‘Gas- en elektriciteitsverbruik”. [Online Image]. Gas usage in the winter higher than in the summer.

There is a direct correlation between the low outside temperature and the natural gas use for the heating of houses. The gas used for cooking and water heating is almost constant during the year (Ekentis, 2020).

The benefit of a reliable natural gas grid is the continuous delivery of natural gas at all times. Within the built environment, natural gas is used for space heating, domestic water heating, and cooking. The benefit of a reliable natural gas system is the continuous delivery of these services. There is a direct correlation between the outside temperature and gas use. Cold periods will cause a peak demand for natural gas in the residential area. Consequently, the needed production (and transmission) capacity and the level of reliability is determined based on the amount of gas needed for space heating during extremely low temperatures. In case the supply in the energy system decreases, constraints on the demand side are necessary to make sure the system remains reliable. The constraints should apply during cold periods. An essential condition of a useful demand constraint is that the constraint should significantly reduce the amount of energy used in the residential area. Otherwise, there will be no match between supply and demand.

Wei, et al. (2014) state that turning the indoor temperature down or even off can be an effective way to reduce the amount of energy. Also, not heating all the rooms in the house, for example, when they are not occupied, is an efficient way to save energy. Milieu Centraal (n.d.) indicates that by lowering the indoor temperature with 1°C, natural gas use can be reduced by around 6%. Turning down the temperature of rooms that are not regularly occupied can reduce the energy demand even further, by around 15% (Milieu Centraal, n.d.). A lower indoor temperature or fewer rooms heated within a house will reduce the amount of natural gas used, can be effective measures to ensure the match between supply and demand.

Next to the fact that the reduction of the indoor temperature and in the number of rooms that are heating can lead to a drop in energy use, a great preference heterogeneity exist in the preferred temperature and rooms that are heated.

First, the preferred indoor temperature is analyzed. The goal of space heating is to keep the house and rooms thermally comfortable. The thermal temperature inside is a big driver to increase the demand for natural gas by households (Wei, et al. 2018). One of the main parameters to define the thermal comfort is the air temperature inside. Therefore, it is possible to use the temperature indoors as the parameter of thermal comfort (Yohanis & Mondol, 2010). The average temperature indoor depends on the preferences of the households. A wide range is given for the preferred indoor temperature in literature. The preferred temperature is mainly influenced by the occupancy of the house and the perception of the household. Literature indicates that several households still prefer a minimum indoor temperature of 17°C (Santamoris, et al., 2014; Schellen, et, al., 2010). The maximum indoor temperature maintained is indicated at 23°C (Conner & Lucas, 1990; Yohanis & Mandol, 2010). The average indoor temperature is between 19°C and 20 °C (Yohanis & Mandol, 2010; Wei, et al. 2014).

Besides the variation in the desired indoor temperature, a significant difference in the temperature between rooms exists. Several studies have shown that there is a correlation between the space-heating behavior and room type. The research of Wei et al. (2018) summarizes all these findings and states that generally, the living room has a higher temperature than other rooms within the house. Connar and Lucas (1990) even state that within the US, the living room is generally 2°C warmer than bedrooms and even 6°C warmer than basements. Yohanis & Mondol (2010) found out that living rooms in the UK tend to have the highest temperature during the winter, followed by the kitchen and bedrooms. The occupancy of the room can explain the difference in room temperature. A higher occupancy of the room generally means a higher temperature of the room. Yohanis & Mondol (2010) analyzed the difference between the temperature in bedrooms of several houses within the UK. They concluded that the average bedroom temperature varies between 14,1°C and 24,6°C, which implies a difference of 10°C (Yohanis & Mondol, 2010).

There is a great variance in the maintained indoor temperature and the number of specific rooms heated between households. Households do not prefer one specific indoor temperature. Moreover, households maintain different temperatures in rooms. Therefore, this report expects there is not much resistance when reducing the indoor temperature with 1°C or 2°C or the number of rooms that can be heated. Furthermore, lowering these variables can create a reduction in the amount of gas that is used. Constraining these variables can create some flexibility in the demand. Flexible demand can be used to match supply and demand in a more demand-oriented way during shortages. The stated choice experiment will use these variables as attributes. Chapter 5 will construct the stated choice experiment. The variables display part of the decrease in the level of reliability on the supply side. This research will only focus on reducing indoor temperature since when the thermostat is completely turned off during very cold periods freezing damage might occur. Furthermore, a too low indoor temperature causes that it will not be comfortable at home and might even cause health risks (Santamouris, et al. 2014). Finally, it is almost impossible to restrict the hydrogen use of households due to EU codes. The households are protected from the restriction of energy.

The flexible demand used to help to realize a match between supply and demand can be seen as a form of demand-side management. The demand-side management in a system used for heating differs from the demand-side management known from the electricity domain. Gas has a less fluctuating price than electricity. Furthermore, switching the use of gas to other periods is more difficult compared to the use of electricity. Turning on electrical devices can easily be done during periods with less demand (during the night), while warming houses during peak demand (cold periods) is not something that can be shifted easily to periods with less demand (warmer periods). This research analyzes the preferences of households related to the reliability and affordability of a hydrogen system. It determines the households' WTP for reliability. This research might identify the need to create a more affordable system. In that case, the reliability regulations must not only focus on the supply but also look at other possibilities to guarantee a match between supply and demand. This research creates insights into the usage of the demand of households to match supply and demand. Reducing demand during shortages can help create a match between supply and demand, while there is no need to construct immense generation facilities. In the electricity domain, the use of demand to ensure a reliable system is called demand-side management. However, due to the difference between the electricity and the heating system, this research chooses not to use the term "demand-side management."

2.4 Factors influencing Willingness To Pay for reliable energy systems and the preference of a hydrogen system

This research focuses on the trade-off of the households between the affordability and reliability of the hydrogen system. The average WTP for reliability is determined. The natural gas system and the hydrogen system deliver gas to every affiliate. In this research, every affiliate to the gas system is a household. Each household uses a different amount of natural gas. The space heating behavior of households primarily influences the amount of gas used. For example, the indoor temperature maintained varies between houses. One household might prefer a low indoor temperature while another individual might desire a high indoor temperature. Consequently, the individual preferring a low indoor temperature has less benefit from an infrastructure that can always deliver natural gas to heat the house until very high temperatures. The difference in benefit implies a difference in utility obtained from a reliable gas system between households. Therefore, it is expected that different factors influence the WTP for a reliable system used for heating.

This section will discuss the factors influencing the WTP. First, one can expect that heating habits and housing characteristics of households influence the WTP for the reliability or the choice for a hydrogen system with a lower level of reliability. Sub-section 2.4.1 elaborates on this influence. Secondly, one can expect that the socio-economic and demographic characteristics of households influence the WTP for the reliability or the willingness to choose a hydrogen system with a lower level of reliability. Sub-section 2.4.2 discusses these characteristics. Finally, sub-section 2.4.3 looks into the influence of attitudes towards sustainability and hydrogen. It is expected that the attitudes will affect the WTP for reliability and the choice for a hydrogen system with a lower level of reliability.

2.4.1 Influence of the heating habits and housing characteristics of the WTP and preference of households

As indicated in section 2.3, different heating habits exist for the indoor temperature, and a wide range of maintained indoor temperature is indicated. Based on the wide range of maintained indoor temperatures, it is expected that households that maintain a higher indoor temperature obtain more utility from a reliable system used for heating. Consequently, the WTP for a reliable energy system is higher. Furthermore, due to a higher utility, this research expects that households maintaining a higher indoor temperature dislike a system with a lower level of reliability.

The literature identifies different factors that influence the maintained indoor temperature. First, most households want to keep their homes at different temperatures during day and night. Generally, the temperature during the night is a few degrees lower (Wei, et al., 2018; Yohanis & Mondol, 2010). Another factor influencing the indoor temperature is the occupancy of the household. Households that are generally at home will maintain a higher temperature than households that generally away from home (Wei, et al., 2018). It is expected that households away from home more often experience less utility from a reliable energy system. In addition to that, they have a lower WTP for reliability. Moreover, they will like a hydrogen system with a lower level of reliability than households more often at home. For this factor, it is essential to ask about the occupancy situation before the COVID-19 crisis. Due to this crisis, everyone is at home more often, and this will say less about the regular occupancy situation and the possible relation with the choice for a less reliable energy system.

Different measures can be taken by households to save energy. Examples of measures that influence energy use are lower the indoor temperature when at home and reduce the temperature when leaving the house. Other simple measures would be to close the window before increasing the indoor temperature or shower during a shorter period (Milieu Centraal, n.d.). The households that take measures to reduce their energy use will have several reasons, such as reducing the energy costs or reducing their carbon footprint. It is expected that households who already take measures to reduce their energy use will be more sensitive for price reductions and have a lower WTP for reliability. Furthermore, it is expected that this group will choose more often for a hydrogen system with a lower level of reliability.

Another factor that might influence the WTP for reliability would be the households' insight into their gas use. Several households are not aware of their actual energy costs, for example, households who pay a fixed amount of rent every month, including their energy use. It is expected that these households will be less sensitive to price reductions because they are not aware of the actual energy costs. Therefore, it is expected that the households with no insight into their energy bill will have a higher WTP for reliability and dislike using a hydrogen system with a reduced level of reliability.

Also, house characteristics can influence the amount of energy used—for example, the quality of insulation influences energy use. There is a correlation between the decrease in indoor temperature and thermal losses (Santamouris, et al. 2014). The energy use will be higher in buildings with bad insulation since more energy is needed to keep the house at the same indoor temperature than a house that is better insulated. It is expected that households living in a poorly insulated house are more willing to pay for reliability and dislike a heating alternative with a lower level of reliability.

Around 95% of the complete housing stock in the Netherlands is connected to the natural gas grid. Around 5% of the housing stock has different connections to get their heat. The houses that are not connected to the natural gas grid get their warmth from other, probably sustainable sources. This research expects that households that are not connected to the natural gas grid have less affinity with the natural gas grid or are frontrunners in the energy transition of the built environment. Therefore, they are willing to choose a sustainable hydrogen alternative, even with a reduced level of reliability.

Finally, the building year of a house can say things about the current condition of a house. Houses built before 1970 have generally not a good quality of insulation. Therefore, more energy is used to keep the house thermally comfortable. Houses built after 1970 are better insulated, double glazing and roof and cavity wall insulation became more standard in houses. The houses built after 1990 especially have low costs for energy use. In 1990 the building agreement was implemented, and more quality rules became applicable (Hubbs, n.d.). The housing stock built long ago usually has a bad quality of insulation and has a higher energy use to keep the house thermally comfortable. It is expected that households living in these houses obtain more utility from a system with a high level of reliability. Concludingly, it is expected that these households have a higher WTP for reliability and dislike a hydrogen system with a lower level of reliability.

2.4.2 Influence of the socio-demographic and economic variables on the WTP and preference of households

Next to the heating habits and the housing characteristics, it can be assumed that the WTP for a reliable gas system and that the trade-off between a reliable and cost-effective hydrogen system is based on the socio-economic and demographic characteristics of households. Furthermore, it is expected that socio-demographic and economic variables influence the preference for an alternative hydrogen design.

A commonly mentioned influencing factor is the income of the households. The WTP for reliable energy services can be constraint by income. The WTP can increases until the cost of the service outreached the budget for energy (Gill, et al., 2017). Households with a higher income will probably not be constraint by their budget and have a slightly higher WTP. Furthermore, households with a higher income are generally more optimistic about sustainable heating systems than inhabitants with a lower income (SCP, 2018). This statement implies that higher-income groups prefer a hydrogen system with a lower level of reliability. Therefore, this research expects that households with a higher income are generally less sensitive to the price of energy systems, but prefer an alternative hydrogen design.

This report also expects that the level of education influences the WTP for a reliable energy system. Guerra-Santin and Itard (2010) indicated that inhabitants with a higher education degree have less often a very high indoor temperature than inhabitants with a lower education degree. Moreover, generally, inhabitants with a higher education degree are more aware of their energy use. Based on these findings, one expects that households with a lower educational degree have a higher WTP for reliability. When looking at the sustainability side, households with a higher educational level are generally more concerned with climate change and are more willing to participate in the transition to sustainable heating alternatives (SCP, 2020). Therefore, this thesis expects that households with a higher educational level more often choose an alternative hydrogen design. However, it would be interesting to find out if this group also more often choose a hydrogen system with a lower level of reliability.

Thirdly, this research expects that the household size influences the WTP. For example, when a household consist of more people, an interruption of the system will influence a greater group of individuals. The utility of this household obtained by overcoming such an interruption by a reliable energy system is higher than for smaller households. Therefore one can assume that a greater household has a higher WTP for a reliable energy system (Morrissey, et al., 2018).

Also, age can be an influencing factor on the WTP for reliability. Morrissey, et al. (2018) investigated the factors influencing the WTP of households to avoid power outages in the UK, where electricity is the primary resource for the heating of the built environment. This research shows that older citizens (especially the citizens of 65 and older) have a lower WTP for a reliable energy system than younger citizens. A possible explanation given is that older citizens have experienced a less reliable energy system in the past and, in addition to that, see less severe consequences of a reduction in the reliability (Morrisey, et al., 2018). Another explanation could be that older inhabitants generally experience the benefit of a reliable, sustainable energy system for a shorter period. Simply because their life expectancy is shorter from the moment the hydrogen system is laid down. On the other hand, younger adults (18 – 25 years old) have a more positive attitude towards a heating system without natural gas than older citizens (SCP, 2020). It is expected that younger adults more often choose an alternative hydrogen system. However, it would be interesting if the younger age group also choose more often for a hydrogen system with a lower level of reliability.

Furthermore, this thesis expects that homeowners are less willing to change their energy system since they need to renovate their own house instead of asking their housing corporation or landlord for renovations. They will see the direct bill of the transition and will be more conservative in changing the energy connection (SCP, 2020). Therefore, this report expects that homeowners will less often choose an alternative hydrogen design.

The gender of the respondents may also influence the WTP. However, different opinions about the influence exist. On the one hand, literature mentions that females generally prefer a higher indoor temperature (Wei, et al., 2018). The preference for a higher indoor temperature would imply that females have a higher utility and have a higher WTP for reliable energy systems. On the other hand, literature states that males use their thermostats more often (Wei, et al., 2018) and maintain their homes at the temperature they prefer during that moment. The varying indoor temperature would imply that males have a slightly higher utility and WTP for reliability. When looking at the sustainability aspect, the recent research of the SCP (2020) showed that females are generally more positive about a sustainable system used for heating. Females are more willing to step away from natural gas (SCP, 2020). In this respect, one expects that females more often choose for a hydrogen design, but it is unknown whether males or females more often choose a hydrogen system with a lower level of reliability. Moreover, whether males or females have a higher WTP for a reliable energy system is unknown.

Finally, this report expects that the living area of the households will influence the utility obtained from reliability. Houses in rural areas are more sensitive to the leakage of energy. Generally, rural areas consist of more free-standing houses, and there is less necessity to build smaller houses or apartments. Bigger houses need more energy to keep the house warm. Houses and apartments in urban areas are usually compact constructions and are build against each other. The warmth from the neighboring houses will help keep the surrounding houses thermally comfortable (McLendon, 2018). Generally, the amount of energy that is leaked is higher in rural areas than in urban areas. Therefore, more natural gas is used in rural areas, which creates a higher utility for reliable energy systems. Subsequently, this report expects that the WTP for reliability and the preference for a system with a higher level of reliability is slightly higher in rural areas than in urban areas. On the other hand, from research, it became apparent that inhabitants of urban areas are more concerned with climate change since they experience more negative side effects of environmental issues, such as air pollution. Furthermore, more younger people, who are more concerned about climate change live in urban areas (SCP, 2020). It is expected that households living in urban areas more often choose for a hydrogen system due to climate concerns, but whether they prefer a hydrogen system with a lower level of reliability is unknown.

2.4.3 Influence of attitudes on the WTP and preference of households

This thesis expects that the attitudes and personal beliefs also influence the preference of the households (Franceschinis, et al., 2017; Hansla, et al. 2008). Willingness to participate in the energy transition and ensure the built environment switches from natural gas to a sustainable alternative is a necessary condition to induce change (SCP, 2020). The Sociaal Plan Bureau (2020) indicated that the WTP for sustainable energy in the residential area is related to different concerns, such as concerns about whether the sustainable resources are sufficiently effective or concerns about future developments of the chosen sustainable energy source. Problem awareness and the willingness to take action are connected to support for climate policies and the use of sustainable resources. There is a strong correlation between the support for the energy transition and the intention to cut off the residential area from natural gas (SCP, 2020). The attitude towards sustainability influences the support for the energy transition and the use of hydrogen in the residential areas. Nevertheless, the influence of attitudes on the preference for a hydrogen system with a lower level of reliability is unknown.

This research also expects that households who expect hydrogen to be dangerous or very expensive have negative associations with hydrogen. Therefore, they will be less willing to use hydrogen as a heating fuel to heat their house. Subsequently, they are less willing to choose a hydrogen system with a reduced level of reliability and cost.

Innovation research identifies different kinds of adopters. The commonly used innovation theory of Roger (2003) identifies five different kinds of adopters: innovators, early adopters, early majority, late majority, and laggards. Innovators and early adopters are less concerned about problems and want to test new technologies. The innovation in this research is a hydrogen system, with a reduced level of reliability. This research will probably identify adopters, followers, and laggards based on their attitudes towards sustainable heating and hydrogen. This thesis expects that households that are more willing to use sustainable heating and are more optimistic about hydrogen can be characterized as “frontrunners” in the energy transition (SCP, 2020). They are the adaptors of the new system. “Frontrunners” or “adopters” are usually less concerned about problems of innovations. Therefore, this research expects that the “frontrunners” may see a reduced level of reliability, not as a problem. They may see the reduction in reliability as a precondition for the implementation of an affordable hydrogen system.

Furthermore, grid operators, such as Stedin, are not allowed to force households to change their natural gas connection to a sustainable alternative, such as hydrogen. Therefore, it is likely that the first neighbourhoods that will shift from natural gas to hydrogen are willing to participate and have a positive attitude regarding sustainability.

In the coming years, the high upfront investment costs in electrolysers are considered a problem. The electrolysers are built to provide neighbourhoods of hydrogen. There is no national infrastructure that can help to match supply and demand. The WTP for the reliability of this group is essential. They will participate in the transition phase at which the costs are the highest. Their trade-off between reliability and affordability will be crucial for the design of the first hydrogen projects.

The attitudes and beliefs related to hydrogen and sustainability are explanatory variables in this research (SCP, 2020). One knows that households that are more willing to use sustainable heating will choose a hydrogen design instead of a natural gas system. However, it will be interesting to find out if this group also prefers an alternative hydrogen system with a lower level of reliability and what the influence on the WTP for reliability is. Furthermore, it will create insights in the trade-off between reliability and affordability for the design of the first hydrogen projects. The hydrogen infrastructure will start in neighbourhoods with adopters, which may influence the preference for a hydrogen system with a reduced level of reliability and cost.

2.5 Conclusion

This chapter answers the first sub-question. Furthermore, the chapter made a start about which attributes to include in the stated preference experiment. The first section characterizes the gas system as a common-pool resource, and the trade-off between reliability and cost is analyzed. After that, the usage of demand to create a match between supply and demand is discussed. Finally, the chapter elaborates on different factors that may influence the Willingness To Pay (WTP) for reliability and the preference for a hydrogen system with a lower level of reliability.

- The first sub-question is:

"*What characterizes the relationship between the cost and reliability of energy systems?*"

There is no one on one relationship between the investment cost of the grid operators and the benefits of the households, caused by the fact that the gas system is a common-pool resource. The benefits of the households should be considered to get insights into the investments needed in the gas network. Improved reliability of the energy system leads to higher investment costs. The households must be willing to pay for the improved reliability of the energy system at higher costs

Literature shows that an increasing level of reliability in energy systems comes with higher costs. Therefore, a system is never 100% reliable. 100% reliable is over reliable and too expensive. Especially the last part of creating a 100% reliable energy system is very costly. The term reliability is strongly related to the needs of the households. Reliable energy systems deliver the quantity and quality of energy when desired by households. Furthermore, the investment costs in energy systems are eventually be paid for by households. So the cost of an energy system at a certain level of reliability is the expense of the households.

The system used for heating is an energy system, and the demand should match the supply. When decreasing the supply, grid operators must create flexibility on the demand side to prevent interruptions in the system. The natural gas system, with a high level of reliability, is laid down to overcome interruptions during extreme circumstances (extreme low outside temperatures). The main benefit of a reliable gas system is the continuous delivery of the services of natural gas at all times. Thus, the continuous delivery of gas for space heating, domestic water heating, and cooking.

Reducing the maximum indoor temperature and the number of rooms that are allowed to be heated during peak demand can significantly reduce the usage of gas. Moreover, there is much heterogeneity between households about the preferred indoor temperature and the number of rooms heated. Combining gives that these variables seem effective ways to create demand flexibility and to reduce the reliance of the supply. Chapter 5 will use both attributes to set up the stated choice experiment.

The utility obtained from reliability and the WTP for reliability differs per household. Different factors are identified that may influence the WTP for reliability and the choice for an alternative hydrogen design with a lower level of reliability.

3. Technical options hydrogen infrastructure

This chapter discusses the technical options for reducing the reliability of the hydrogen infrastructure used for heating. Since this research only focusses on low-temperature heating, which is the heating of residential areas, the options of a hydrogen system used for low-temperature heating will be analyzed. First, section 3.1 gives an introduction to hydrogen. After that, section 3.2 discusses the cost related to the hydrogen infrastructure. The third section elaborates on the usage of sustainable hydrogen in the built environment. This section includes the changes needed to ensure a system used for heating with a reduced level of reliability can be implemented. The last section gives a conclusion about the technical options and answers the second sub-question.

3.1 Specification of hydrogen for this research

Within the field of energy supply, hydrogen can be seen as a gaseous energy carrier and is comparable to natural gas. Hydrogen cannot be found in nature and needs to be created. A primary advantage of hydrogen is that the combustion of hydrogen does not emit CO_2 emissions, in contrast to natural gas (KIWA, 2018b). However, during the formation of hydrogen, CO_2 emissions can occur. The occurrence of CO_2 emissions during formation is dependent on the way hydrogen is produced. Hydrogen can be made in different ways. First, hydrogen can be created by using fossil fuels, such as natural gas and coal. This hydrogen is called black hydrogen, and by the formation of black hydrogen, CO_2 emissions occur (CIEP, 2019). Currently, the process industry in The Netherlands already uses around 100 PJ of black hydrogen (Klimaatakkoord, 2019).

Another form of hydrogen is blue hydrogen. Blue hydrogen is also made from fossil fuel, but by producing blue hydrogen, carbon capture, utilization, and storage (CCUS) are used to capture the CO_2 emissions. Finally, one can also produce green hydrogen. Green hydrogen is made from sustainable electricity generated from sources such as wind and solar. Electrolysers produce this form of hydrogen (CIEP, 2019). Blue and green hydrogen are seen as sustainable forms of hydrogen that can help to reduce the CO_2 emissions in the built environment in The Netherlands. Both forms of hydrogen can, in the long term play an essential role in becoming CO_2 neutral before 2050 (Klimaatakkoord, 2019). Blue hydrogen using CCUS is seen as the stepping stone from black hydrogen to green hydrogen. It is seen as an essential step to scale up the hydrogen infrastructure and the hydrogen market (DNV GL, 2020).

Currently, The Netherlands does not produce enough sustainable electricity to scale up green hydrogen production immediately. The current electricity mix in the Netherlands contains too much fossil fuels and even contains a large share of coal. The usage of coal will emit even more CO_2 than the current black hydrogen production from natural gas by using the Steam Methane Reforming (SMR) process (TKI, 2018). Green hydrogen is a form of sustainable hydrogen that can be produced both on a large scale and on a smaller scale in local communities. In communities, electricity can be produced locally by solar panels. This sustainable electricity can be converted by using electrolysers to green hydrogen (Van Wijk, 2016).

For the production of green hydrogen, sustainable electricity is converted by electrolysis. A precondition for the production of green hydrogen is that the electricity used is sustainable. The electrolyse process can be performed with technologies at low (60-70°C) or high (600-800°C) temperatures. With both technologies, sustainable electricity is used for the division of water (H_2O) to obtain hydrogen (H_2) and oxygen (O_2). The current load factor for the production of hydrogen from electricity is 72%. This load factor means that 55 kWh electricity is needed to create 1 kg of hydrogen (55kWh/kg H_2). It is expected that in the coming years (in 2030), a load factor of 79% (50 kWh/kg H_2) can be obtained (TKI, 2018).

3.2 Estimating the cost of reliable green hydrogen system

This section analyzes the cost of reliability in a hydrogen system used for heating. The first sub-section analyzes the investment costs of an electrolyser. After that, the production cost is estimated. Finally, the transportation cost will be addressed.

3.2.1 Increasing investment costs for very reliable green hydrogen system

For the construction of electrolysers, upfront investments are needed. The height of the investments depends on the size of the electrolysers. Higher generation capacity of the electrolysers comes with higher investment costs. In Stad aan ‘t Haringvliet the construction cost for an electrolyser is €12.000.000 €/MW (Ekentis, 2020; TKI, 2019). One expects that the construction cost will decrease to €300 - €400/kW in 2030, caused by different pilot installations. In the coming years, also a possibility of economies of scale can be obtained. Economies of scale will ensure that the components necessary for the construction of electrolysers will become less expensive and widely available (TKI, 2019).

The necessary generation capacity depends on the amount of green hydrogen needed during a predefined extreme weather condition that holds for 24-hours. Currently, this temperature is -12℃. Stedin is working on the hydrogen pilot project of Stad aan ‘t Haringvliet. In this project, Stedin will convert the natural gas grid to a grid made suitable for the transportation of green hydrogen. The transition should be ready in 2025 (KIWA & Stedin, 2019). For this project, Stedin developed a curve to determine the amount of green hydrogen needed to serve demand until different temperatures. The following formula defines this curve (Ekentis, 2020):

$$Y = -78X + 1800$$

Y = hydrogen capacity (m^3/h)
X = minimum 24-hour temperature (℃).

Figure 3.1 displays the capacity curve (Groenehuijse, et al., 2019). Stedin developed this curve for the pilot project, and is based on the housing stock of Stad aan ‘t Haringvliet, which is 600 houses.

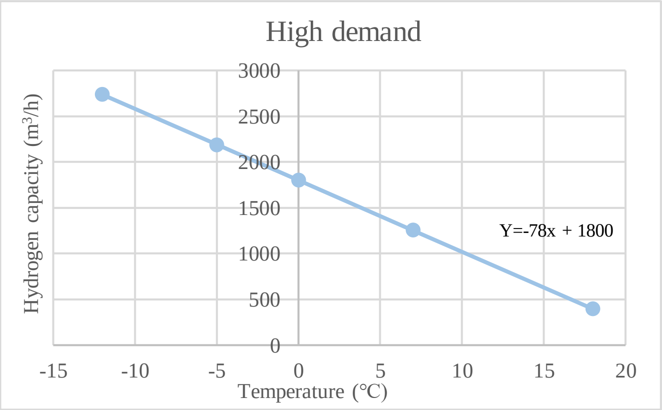

Figure 3.1 - [Linearized capacity curve for high demand.] Retrieved from Groenehuijse, et al. (2019). H2Stad [Graph]

The investment costs for the electrolysers are based on the curve for Stad aan ‘t Haringvliet. This research determines the investment costs for different reliability regulations based on this curve.

The generation capacity needed to serve demand till -12℃ in Stad aan ‘t Haringvliet equals -78*-12+1800 = 2.736 m^3/hour. One must multiply the generation capacity by the density of hydrogen and the load factor to determine the investment cost. For the load factor, the current load factor is used, which is 55 kWh/kg H_2. The density of hydrogen is 0,089 kg/m^3 hydrogen. The electrolyser should be able to produce 13.406,4 kW. Multiplying the generation capacity with the construction cost of 12.000.000 €/MW (Ekentis, 2020) implies that the investment cost of an electrolyser that serves the demand untill -12℃ is approximately €16 million.

In this way, the construction cost of electrolysers serving demand until different outside temperatures can be calculated. The investment cost of an electrolyser that serves demand until -7℃ is approximately €13,8 million. The investment costs imply that the construction cost of an electrolyser that serves demand until -7℃ is almost 15% cheaper than the cost of an electrolyser that meets demand -12℃ in Stad aan ‘t Haringvliet.

The investment costs can also be calculated based on the expectations for 2030, namely with the expected lowering in construction cost to 300-400 €/kW, and the load factor of 50 kWh/kg H_2. With these expectations, an electrolyser serving demand until -12℃ will cost in the range €3,7 - €4,9 million. An electrolyser serving demand until -7℃ will cost approximately €3,1 - €4,2 million. This expectation also results in a cost reduction of 15%.

3.2.2 Influence of production cost for reliable green hydrogen system

Electricity is needed for the production of green hydrogen. Therefore, the cost of green hydrogen will depend on the electricity price. The price developments of electricity are essential for the competitiveness of green hydrogen. Moreover, the type of price paid for electricity is important. In principle, a lower price is used for a higher purchase of electricity. With the large-scale conversion, Power Purchase Agreements (PPAs) can be concluded through which a lower electricity price can be obtained than the average production cost of electricity (TKI, 2018). In 2030 the wholesale price of electricity is expected to be 57 €/MWh (PBL, 2019). The load factor for the conversation of electricity to green hydrogen is expected to be 55 kWh/kg H_2 in 2030, which is equal to 0,05 MWh/kg H_2. Multiplying the expected conversion factor with the expected electricity prices implies an expected price of 2,85 €/kg H_2. The density of hydrogen equals 0,089 kg/m^3. The price of green hydrogen is expected to be 0,25 €/m^3.

The price of green hydrogen should be multiplied by three to compare the price to the price of natural gas. The price must be multiplied by three since hydrogen has three times less energy value than natural gas (Groenhuijse, et al. 2003). Subsequently, 0,75 € should be paid for the generation of hydrogen to obtain the same amount of energy. This price does not include any construction costs for the electrolyser. The current average price for natural gas is 0,814 €/m^3 (Milieucentraal, 2020). This price is not just the gas price but includes different forms of taxes. The pre-tax price for natural gas is around 0,32 €/m^3. The taxes on natural gas are €0,50/$m^{3,}$ from which 21% (around 0,11 €/m^3) is VAT (Milieucentraal, 2020). The other 79% (0,39 €/m^3) of the tax on natural gas can, in the future, be raised to make natural gas more expensive than green hydrogen. This tax is levied for the support of sustainable energy sources and to reduce the CO_2 emissions caused by natural gas.

Besides producing green hydrogen from sustainable electricity in the Netherlands, producing green hydrogen and generating sustainable electricity can be done in different places over the world. Typically these places have many sun hours, such as Australia or the Sahara. The green electricity generated by solar panels can be converted to green hydrogen and transported to Europe. The solar electricity generated will have a very low price, since much solar energy can be generated all over the year. In the Sahara, the sun is around during the summer and winter periods. The Netherlands imports 60% of its energy, and a significant part of the natural gas import comes from Algeria and Libya. Pipes transport natural gas. These pipes can be used to transport green hydrogen as well (Van Wijk, 2019). By importing green hydrogen from countries with many sun hours and in addition to that with a very low sustainable electricity price, the green hydrogen can be produced at a lower price. Consequently, it can become cost-effective and compatible with other sources on the Dutch energy market.

3.2.3 Influence of transportation cost for reliable green hydrogen system

With a few adjustments, hydrogen can be transported by the natural gas grid. The natural gas grid has enough transportation capacity to fulfill the current reliability regulations. However, as mentioned before, the energy density of hydrogen is three times lower than that of natural gas. The lower energy density means that the gas grid should transport three times more hydrogen with consistent demand than natural gas. The physical properties of hydrogen should be compared to natural gas. Based on this comparison, it can be concluded that in the case of hydrogen distribution, the capacity of the gas grid is barely lower than that of the natural gas distribution (Pulles, 2020). Two explanations will be given below.

The first explanation relates to the fact that the pressure loss in a tube is proportional to the dynamic pressure according to the formula:

$$\Delta P = \frac{1}{2} r v^2 \ .$$

The specific gravity of hydrogen is around nine times smaller than that of natural gas. Therefore, with a density (r) that is nine times lower and a velocity (v) that is three times higher, the pressure loss (ΔP) remains the same for hydrogen.

The lower energy density of hydrogen causes the increase in velocity by a factor 3. The current legislation state that the maximal gas velocity in pipes is 30 m/s. The exact reason for this maximum speed is not documented, but it is assumed that the risk of noise pollution causes it. However, noise pollution is not only depended on the velocity, but also the density of the gas. Therefore, one expects that increasing the gas velocity with a factor 3 will not lead to severe noise nuisance (Pulles, 2020).

There is also another reasoning to explain that the capacity of the gas grid remains equal. The capacity of the gas grid is proportional to the Wobbe-Index (W). The Wobbe-Index of pure hydrogen is around 10% higher than that of natural gas. However, the Wobbe-Index should be corrected because gases will behave differently than ideal gases during higher pressures. For natural gas, the rule applies that with every pressure increase of 1 bar, 0,2% extra capacity is created. With hydrogen, this is the other way around. A pressure increase of 1 bar will cause a capacity loss of 0,04%. With a pressure grid of 8 bar, 1,9% of the indicated 10% capacity profit based on the Wobbe-Index is negated. The Wobbe-Index should also be corrected for the pipe friction factor. The capacity of the pipe is inversely proportional to the friction factor. Based on the report of Pulles (2020), a loss for the pipe friction for hydrogen compared to natural gas is around 20% for plastic pipelines. All this summed up results in a net loss of the distribution capacity of hydrogen compared to natural gas of around 10%, with a three times higher velocity and a pressure of 8 bar (Pulles, 2020). The natural gas distribution network is highly over-dimensioned, which implies that the capacity of the tubes for the transportation of hydrogen will not cause any problems.

Several studies have indicated a limited effect of hydrogen on the current grid materials that the current gas distribution grid materials are suitable to transport hydrogen. The published studies showed that no degradation of plastic and rubber distribution materials occurred due to hydrogen. Furthermore, the gas distribution metals such as (stainless) steel and cast iron do not show hydrogen embrittlement by the transportation of hydrogen. Lastly, copper, brass, and aluminum are not affected by hydrogen. However, the question remains whether the studies were performed over a sufficient period to be sure about the long-term behavior of the distribution materials (KIWA, 2018b).

Based on these findings, it is expected that not much extra cost needs to be made to create a reliable hydrogen transportation grid. The capacity needed for hydrogen remains the same as the current capacity for natural gas. Only adjustment costs are needed. However, adjustment cost is needed to transform the natural gas grid into a hydrogen grid with any chosen level of reliability.

Besides the transportation of hydrogen through the natural gas grid, hydrogen cylinders can also be seen as alternative transportation mean. Hydrogen cylinders may function as a buffer in case the hydrogen demand exceeds the hydrogen supply.

The current gas grid design is based on the amount of gas used during an outside temperature of -12℃. During -12℃, the amount of gas used per house is around 1,3 m^3/h (Koppenol, 2016). When using cylinders at home to store hydrogen, the cylinders must not be too heavy. Otherwise, it would be impossible for households to change these cylinders. Consequently, this research uses cylinders that weigh around 20 kg. These cylinders can store around 1,8m^3 hydrogen (IJsfabriek Strombeek, 2018). The cylinders must act as buffer capacity, and they need to heat the houses during periods with an outside temperature of -12℃. When comparing the amount of gas used during -12℃ (1,3m^3/h) and the amount of hydrogen that can be stored in the hydrogen cylinders (1,8m^3), one can conclude that the hydrogen cylinders need to be replaced almost every hour. Replacing the cylinders every hour will cause many inconveniences to the households. Moreover, an enormous space inside or outside the house is needed to store all these hydrogen cylinders. Finally, more safety risks occur when households must change the hydrogen cylinders themselves. Hydrogen should be carefully managed and always be properly connected and sealed. Therefore, this research does not incorporate the option to deliver hydrogen to the households by cylinders. Thus for the transportation of gas, only the gas grid will be used.

Concludingly, not many additional costs are expected for the transportation of hydrogen in a very reliable grid. Moreover, it is expected that the marginal price for hydrogen in the longer term will not differ much from the current natural gas price. However, a lot of cost difference is created when bigger electrolysers need to be built to maintain a high level of reliability. Therefore, this research bases the cost for reliability on the investments of the electrolysers.

3.3 Hydrogen in the built environment

This subsection discusses the use of hydrogen in the built environment. First, this section elaborates on the usage of hydrogen in the built environment. After that, other heating alternatives are compared to hydrogen. Finally, the section discusses several adjustments needed in the hydrogen system to equally distribute the gas of the system with a reduced level of reliability.

3.3.1 Usage of hydrogen in the residential area

Most of the housing stock uses a gas boiler to transfer natural gas into heat. In the gas boiler, cold water is heated with a burner running on natural gas. A pump circulates the warm water to the elements that are used for heating. These could be the radiators, convectors, floor heating, or hot air heating. A thermostat is used to manage the indoor temperature. When the CV-boiler gets a sign from the thermostat that the temperature should increase, the burner will light (by using natural gas), and the cv-water will run through the boiler (Feiken, 2020).

Most houses use a combi boiler. A combi boiler heats the space as well as the tap water. When using a combi boiler, the boiler switches to the warm water program if the households ask for warm tap water. The combi boiler will start again with space heating when the water program is shut down. In a combi boiler, the simultaneous demand for increasing temperature and warm tap water will cause a more extended period when natural gas is needed. First, natural gas is needed to warm up the tap water. After that, natural gas is needed for space heating (Feiken, 2020).

Boilers using hydrogen instead of natural gas will be used in the same way, only the used burners in the cv boilers need to be adjusted for the use of hydrogen (KIWA, 2018b). There are also other options for using hydrogen as heating feedstock in the built environment, which will be discussed in the next section. Because hydrogen can be used in the same way as natural gas (in combi cv boilers), the use of warm tap water simultaneously as heating the house can cause gas demand over a more extended period. Most of the warm tap water is used for showering (Bleekhuis, 2017). Therefore, in extreme cold periods, it might be interesting to find out whether households are willing to shower during times when less natural gas is used. For example, during the times most households are sleeping. During these times, the indoor temperature is generally lower than during the morning. Moreover, it would be interesting to find out whether households that are willing to shower during the night are also less willing to pay for reliability.

3.3.2 Hydrogen compared to heating alternatives

The main advantage of using hydrogen in the built environment is that the existing natural gas infrastructure can be used. Furthermore, only a few adjustments within houses are needed (TNO, 2020; Stedin, 2020). The CV-boiler needs to be changed since the gas burners are not equipped to run on 100% hydrogen. The adjustment of CV boilers is caused by the significantly higher burning velocity of hydrogen than natural gas. The higher burning velocity can cause possible damage to the burner (KIWA, 2018b). Sustainable gasses, such as hydrogen, can especially be a good alternative for neighbourhoods that are very difficult to heat by using all-electric or a heating grid. This sub-section discusses the different heating options to explain when to use different forms of heating alternatives.

All-electric

When considering heating by complete electrification, the primary condition is that the houses should be sufficiently isolated. Furthermore, the heating output installation indoors should be appropriate for all-electric heating. When the isolation or the appropriate output heating installation is insufficiently presented in a house, costly investments are needed. Therefore, the complete electrification of houses is not always a proper alternative, especially in older houses (Stedin, 2020; TNO,2020).

Heating grid

Another alternative is heating by using a heating grid. The needed adjustments indoors with this alternative are a lot less compared to heating by complete electrification. Neighbourhoods with a high population density are especially suitable for heating grids. A possible disadvantage is, however, that a suitable heating source is not always nearby and that the construction of a heating grid is costly. Furthermore, a heating grid is characterized by high connection and formalization fees and high heating tariffs. Important to note is that a heating grid is not per definition sustainable, and the creation of sustainable heating grids is still a challenge in the Netherlands (Stedin, 2020; TNO, 2020).

Hydrogen

The necessary adjustments for the use of hydrogen in the built environment are limited (TNO, 2020). When 100% hydrogen is distributed to the houses, the hydrogen can be converted to heat by using a gas boiler, a hybrid heating pump, or domestic fuel cells. The use of a gas boiler on hydrogen is the same as the current cv-boiler, but it uses hydrogen instead of natural gas to heat the house. The hybrid heating pump is a collaboration between electricity and hydrogen. Most of the heating demand is delivered by electricity, but when the demand is too high and much capacity is needed, the heating pump will use hydrogen. Hydrogen will be used during cold outside temperatures. A last, not well-known alternative is the use of domestic fuel cells to heat the house. This fuel cell generates electricity and warmth from hydrogen. The cost of this technology is still very high (Stedin, 2020). All the technologies make use of 100% hydrogen.

Green gas

When green gases are used as a heating alternative in the built environment, the necessary adjustments are also limited. Green gas can be made from the upgrade of biogas. The main advantage of using green gas is that green gas is methane, just like natural gas. The green gas can be injected in the gas grid, and the grid can be used for the simultaneous transportation of green gas and hydrogen. The cooking devices and the cv-boilers do not have to be adjusted for the use of green gas. However, the main disadvantage of green gas is the limited production of biogas. An upgrade of biogas creates green gas. The combustion of biomass produces biogas. It will not be possible to solely use green gas as a heating fuel (Stedin, 2018b). Furthermore, there are different opinions about the sustainability of green gas.

3.3.3 Technical options to reduce the level of reliability of a hydrogen system

At the moment, grid operators are legally and technically unable to change the amount of gas distributed to the residential area. Furthermore, it is technically impossible to reduce the amount of hydrogen transported to individual houses during periods with high demand. The distribution system does not include any restrictions mechanism. Furthermore, there is no central fuse as in the electricity system that can be shut down if an individual house uses too much electricity. More gas is used and distributed if the demand for natural gas increases.

Also according to the law, the grid operators are not allowed to enforce limitations to their end-user by changing the capacity of their connections. The grid operator is not able to reduce the gas capacity to the end-user and always needs to deliver until the agreed minimum temperature (Overheid, 2018). Consequently, it is currently impossible to distribute an equally and limited amount of capacity to all the houses.

Overcoming this problem is essential if there is chosen for a reduction in the reliability of a hydrogen design. With a lower level of reliability, it should be prevented that one household can maximize its gas demand (maintain a high temperature indoor) while another household will not be able to warm its house till a minimum acceptable indoor temperature. The hydrogen should be equally distributed among all the affiliates.

There are different ways to reduce the demand of households during peak hours. Grid operators can stimulate households to use less hydrogen during peak hours. First, financial incentives can be given. However, the system cannot be built upon these incentives alone. If all households determine to use much hydrogen during peak hours, the system will not have enough generation capacity. Another way would be to create contracts. In these contracts, financial compensation and fees should be determined. The financial compensation will be given to households that want to use less hydrogen during peak hours. Fines will be imposed on households that do not hold to the concluded agreements and use more gas than agreed. Since it is possible to look at the exact gas usage of individual houses afterward, it is possible to impose such fines. If these fines are high enough, it is expected that households will keep to their agreements. With higher sanctions, more compliance is created. Households must see the fine not as a compensatory fine for their behavior. Too low sanctions or compensatory fines might lead to counter effects, and households will just pay off their undesired behavior (Kurz, et al, 2014).

Another way to make sure the constrained gas is distributed equally among the affiliates is by using technical constraints in the distribution grid. The constraint is added to the distribution grid at the connection point from the house to the grid. The technical constraint ensures that households do not use more hydrogen than agreed. The constraint can, for example, ensure that not more than 1 m^3 hydrogen per hour is distributed to the house. The technical design of the constraint should be researched.

Finally, the hydrogen demand can also be changed by using different hydrogen heating systems inside the houses. When grid operators install a hybrid heating pump or a boiler, the hydrogen use is more spread in time. Hybrid heating pumps use next to hydrogen other heating fuels, such as electricity. Therefore, hybrid heating pumps can spread the demand for hydrogen. Furthermore, in a boiler, hydrogen heats the water. Water is a medium that can trap the heat so it can be used over a more extended period. Usually, during the morning and evening, most gas is used. Grid operators can spread the demand during these hours by using these systems. Spreading demand results in less peak demand.

3.4 Conclusion

This section answers the second sub-question. Furthermore, this section elaborates on the other attributes included in the stated choice experiment.

The second sub-question is:
What are the most important technical options to create a design with a reduced level of reliability of a green hydrogen network used for heating?

When analyzing the cost of a hydrogen infrastructure, it becomes apparent that the level of reliability particularly influences the investment cost. A higher level of reliability in the hydrogen system leads to higher upfront investment costs. It is expected that in the long term, the marginal cost of hydrogen can become compatible with natural gas. The natural gas grid can transport the same amount of hydrogen, and only a few adjustments need to be made. Moreover, these adjustments need to be made for every level of reliability. Therefore, it is expected that the reliability level does not significantly influence the transportation cost of hydrogen. Concludingly, the investment costs will primarily influence the cost of reliability in the hydrogen system. Therefore, the cost reductions obtained from lowering the electrolysers' capacity can be used to specify the cost reductions obtained from reducing the reliability.

The gas grid is used for the transportation of sustainable hydrogen. The transportation of hydrogen by cylinders imposes different problems. The gas grid can relatively easily be made suitable for the transportation of hydrogen, and based on different calculations, the grid capacity is sufficient. The use of hydrogen in the built environment results in few adjustments indoors, and insulation is not a pre-condition. Therefore, hydrogen as heating fuel will especially be suitable for older neighbourhoods.

When an alternative design of a hydrogen system is implemented at lower cost and reliability, measures should be taken that the hydrogen is equally distributed among all affiliates. It is technically not possible to lower the transportation capacity to specific houses and give every house the same, constrained amount of hydrogen.

A possible way to reduce the amount of hydrogen transported to individual houses during shortages will be setting up contracts. The contracts will include financial compensation and fines. The fines will be given to the households that did not hold to their agreements and used more gas than agreed. The result of such a breach imposes the possibility that others might not be able to heat their homes due to interruptions in the system. Whether fines will work is a point of discussion, due to the negative side effects of imposing fines. Financial incentives can also stimulate households to decrease their demand during peak hours. However, there is no direct consequence of this measure, and the system must not be built on such a measure.

Another way could be implementing technical constraints in the distribution grid. The technical constraint ensures that households do not use more hydrogen than agreed. The technical design of the constraint should be researched.

Finally, the hydrogen demand can also be changed by using different hydrogen heating systems inside the houses. When grid operators install a hybrid heating pump or a boiler, the hydrogen use is more spread in time. Spreading demand results in less peak demand. These systems and their influence on the demand should be further researched.

4. Discrete choice modeling

This chapter discusses the method used to analyze the preferences of households related to the design of a reliable and cost-effective hydrogen grid. This research is performed to analyze whether households prefer to reduce their hydrogen demand during peak hours in exchange for money. The reduction in hydrogen demand during peak hours can create flexibility in the grid, through which the reliability of the hydrogen system can decrease. Additionally, different factors that might affect the preferences of households are analyzed. Within this research, the preferences of households are revealed by monitoring and analyzing choice behavior. Choice behavior is analyzed by discrete choice modeling (DCM). DCM is used to analyze the choices made by respondents from a set of alternatives and can help to predict choices. The relative influence of the included attributes of the alternatives can be calculated (Koppelman & Bhat, 2006). First, the data collection method is determined. This section discusses the difference between Revealed Preference (RP) and Stated Preference (SP) data. After that, section 4.1 elaborates on the data analysis methods (discrete choice models). This section includes the reasons for the use of DCM instead of other methods.

4.1 Data collection – Stated Choice Experiment

Two ways exist for collecting data for discrete choice modeling; a revealed choice and a stated choice experiment. Revealed preference data consist of data of real-market alternatives and focuses on what people did. Stated preference data concerns non-existing alternatives, attributes, and attributes levels and presents hypothetical surveys to the respondent (Timmermans et al., 1994). This research uses stated preference data instead of revealed preference data. The preferences of households are not included in the current design of infrastructures used for heating, which makes it is impossible to use RP data.

The stated preference data is gathered by using a stated choice experiment spread via a digital survey amongst households. The respondent must be 18 years and older and living in the Netherlands. This report expects that most respondents are not familiar with the transition of the natural gas system towards a sustainable hydrogen system and with the associated trade-off between reliability and cost. Therefore, a short introduction at the beginning of the survey is given. This introduction briefly explains the concept of a hydrogen system used for heating and defines the goal of the survey. The introduction also includes the consequence of the choices in the survey. The addition of consequences to the choices can positively influence the truthful answers of the respondents. Bu indicating that the choices made in the survey will influence the decision-making for the design of the hydrogen grid used for heating creates incentives to the respondents to fill in their real choices. In this way, the survey becomes more consequential.

After the introduction, several choice sets will be presented to the respondent. Each choice set contains three alternatives. Two alternatives present the sustainable hydrogen grid with a lower level of reliability, and the last alternatives always show the current natural gas alternative. In this way, respondents are not forced to choose a sustainable hydrogen grid. Furthermore, adding this choice makes it possible to analyses to which extent the introduction of an alternative hydrogen design (with a lower level of reliability and cost) is preferred above the current situation.

The two sustainable hydrogen systems have different values for the attributes. The attributes to include are based on the literature study from chapters 2 and 3 and considerations of the researcher. For each choice set, respondents are asked to indicate which of the three systems they prefer for the heating of their own house. Besides the choice experiment, also several other questions are included. These questions are needed to determine the influence of demographic variables, the current heating behavior, and the attitude towards hydrogen (discussed in section 2.4). The complete discussion and set up of the survey can be seen in Chapter 5.

4.2 Data analysis - Discrete Choice Model (DCM)

This research uses the concept of DCM instead of asking households directly to their trade-off in, for example, interviews or rating surveys. Different reasons for this choice can be given. Firstly, people do not know their real trade-off if you ask them directly. Secondly, regularly people do not give their true trade-off. Thirdly, judgment is more liable to bias than choices. Lastly, people make choices every day (Chorus, 2018). DCM is an indirect method to ask respondents about their trade-off. For this research, DCM is seen as the appropriate indirect method. From experience, one knows that choosing between alternatives is easier for respondents than, for example, rating parameters from very unattractive to very attractive such as conjoint analysis does (Chorus 2018; Molin, 2018).

This research collects data by observing and collecting the choices of respondents. DCM enables to quantify the values of the respondents given to the different attributes. Furthermore, DCM looks at whether and to what extent households are willing to make a trade-off between a reliable and cost-effective hydrogen system. This research determines the average Willingness To Pay (WTP) for reliable energy systems, while no real market exists for buying reliability. Consequently, no real data market models can be used. DCM calculates the WTP as the increase (or decrease) of one unit in utility divided by the change in utility of the cost coefficient (Chorus, 2018). By calculating the WTP for reliability, the trade-off between cost and reliability can be considered.

The most widely used DCM is based upon the Random Utility Maximization (RUM) model. This RUM model is developed by McFadden (1974). RUM models assume that individuals strive for utility maximization and choose the alternative that maximizes their utility. It assumes the complete rationality of individuals (Train, 2002). Another approach is the Random Regret Minimization (RRM) model (Chorus, 2010). Within the RRM model, the decision rule is not just based on the maximization of utility. The RRM model allows the possibility that the respondent chooses one alternative to avoid negative emotions of the other alternatives. This research bases the discrete choice model on the RUM model. The goal of this research is not analyzing the choice behavior of respondents but looks for the average WTP for a system used for heating. With this goal, the behavioral assumption of complete rationality of individuals is not severe and is an appropriate method to calculate the average WTP.

In each choice set, the respondent can choose between three alternatives: sustainable hydrogen system A, sustainable hydrogen system B, and the current natural gas system. Every alternative has its utility function that calculates the utility of the alternative. The DCM used in this research is based on the RUM theory, so it assumes that the respondent choices the alternative that provides the highest utility.

The most simplistic model is the MNL model. For MNL models, the utility of an alternative is the sum of the systematic utility and the random utility. The systematic utility is predicted by the parameters included in the DCM. The observed factors are the attributes in the choice set and the variables measured in the survey (such as income). The model cannot predict the random utility and is seen as “noise.” This utility is captured in the error term and represents the variability of the total utility of the alternative.

The linear additive utility function of the total utility of a specific alternative is as follows (Chorus, 2018):

$$U_{in} = V_i + \varepsilon_{in} = ASC_{Hydrogen} + \sum\nolimits_m \beta_m * x_{im} + \varepsilon_{in}$$

Where,

i, j	Alternatives i , j
m	Attribute m
U_{in}	N's utility of alternative i
V_i	The systematic utility of alternative i
ε_{in}	The random utility (error term) of alternative i by individual n
β_m	Weight/parameter of attribute m
x_{im}	Attribute level of attribute m of alternative i
$ASC_{Hydrogen}$	Alternative specific constant for hydrogen alternatives (is zero in the natural gas system)

Alternative i is chosen by individual n if (Chorus, 2018):
$ASC_{Hydrogen} + \sum_m \beta_m * x_{im} + \varepsilon_{in} > ASC_{Hydrogen} + \sum_m \beta_m * x_{jm} + \varepsilon_{jn}, \forall j \neq i$

For simplicity reasons, the n is left out, and the following functions can be obtained for the total utility:

$$U_i = V_i + \varepsilon_{in} = \sum\nolimits_m \beta_m * x_{im} + \varepsilon_i$$

With the decision rule:

$\sum_m \beta_m * x_{im} + \varepsilon_i > \sum_m \beta_m * x_{jm} + \varepsilon_j, \forall j \neq i$

By using the maximum likelihood principle, the parameters for all the included attributes (β's) that make your data from the stated preference experiment the most likely can be searched. The parameters of the attributes (β's) display the weight of the observed factor (Koppelman & Bhat, 2006). For labeled alternatives, the researcher can add an alternative specific constant (ASC) to the utility function. The constant captures the utility of the alternative when all parameters of the attributes are zero. Thus, the ASC contains the preference of the respondents that are not explained by the attributes. It is the base utility of one alternative over the other, caused by associations of the labels of the alternatives (Koppelman & Bhat, 2006). In this research, the alternatives are labeled. However, when comparing hydrogen alternatives 1 and 2, these can be seen as unlabeled alternatives. An ASC is added to capture the general preference of a sustainable hydrogen grid over the current natural gas grid. An ACS is added to the utility functions of both sustainable hydrogen alternatives. The following subsection displays the different choice models relevant to this research.

4.2.1 Description of different choice models

The choice probabilities display the chance an alternative is chosen from the choice set by an individual. The utility of the alternatives is used to calculate the choice probabilities. This research searches for the probability that the sustainable hydrogen grid with a lower level in reliability and cost is chosen over the current natural gas grid. An assumption about the probability distribution of the random utility ε is needed to determine the choice probability (Keane, 1997; Koppelman & Bhat, 2006). Below three models with different assumptions are discussed.

Multinomial Logit (MNL) model

The MNL model is the most widely used and is mainly popular due to the simplicity. However, the model makes strong assumptions about the behavior of individuals. The most notable assumption is the Independence of Irrelevant Alternatives (IIA) property. The IIA property assumes that by adding a new alternative to the choice set, the choice probabilities of all other alternatives fall proportionally (Greene & Hensher, 2003; Keane, 1997; Shen, 2009). In MNL models, the ε term of all the alternatives is drawn independently from a distribution with the same variance. The independent draws are known as the i.i.d. error term assumption (Louviere, et al. 2000). The IIA property and the i.i.d. assumption are the main drawbacks of the MNL, but it also causes that the model is simple to estimate since the formula of the choice probabilities is closed form. By applying the logit formula, one can transform the observed utilities into the choice probabilities (Chorus, 2018):

$$P_n(i) = \frac{e^{V_{n,i}}}{\sum_j e^{V_{n,j}}}$$

A way to overcome the IIA property is by using the mixed logit model.

Mixed Logit (ML) model

Due to similarities between alternatives, nesting effects arise. The MNL model assumes there are no correlations between the unobserved utilities (ε) of the alternatives with similar attributes (i.i.d. error term assumption). By wrongly assume that the IIA property holds creates biased parameter estimates. An ML model adds another error component to the utility function that captures the common factors between alternatives (Chorus, 2018; Shen, 2009). The error component displays the utility of the unobserved factors of the hydrogen alternatives. The choice probability can be calculated as follows:

$$P_n(i) = \int_{\upsilon_n} [(P_{n,i}|\upsilon_n) * f(\upsilon_n)] d\upsilon_n$$

Secondly, a mixed logit model captures taste heterogeneity by letting the parameters β vary across individuals. The MNL model wrongly assumes that the β's are fixed and that the taste does not vary across individuals. The choice probability of a mixed logit model that searches for taste heterogeneity can be calculated with:

$$P_n(i) = \int_{\upsilon_n} \int_{\beta_n} [(P_{n,i}|\upsilon_n, \beta_n) * f(\upsilon_n, \beta_n)] d\upsilon_n d\beta_n$$

Furthermore, it is realistic that choices made by the same individual are correlated, since their preference and taste influence their choice. By assuming that these choices are uncorrelated creates underestimated standard errors of the parameters. ML models solve this problem by capturing panel effects. The panel is the complete sequence of the choices made by one individual (Chorus, 2018; Shen, 2009). The choice probability of a mixed logit model that captures all the above mentioned can be calculated by:

$$P_n(i) = \int_{\upsilon_n, \beta_n} (\prod_{t=1}^{T} P_{ni}^{t}|\upsilon_n, \beta_n) * f(\upsilon_n, \beta_n)) d\upsilon_n d\beta_n$$

In which "t" is a choice situation of an individual.

Hybrid model

The last model mentioned in this research is the hybrid choice model. Within the hybrid choice model, a latent variable model is added to the discrete choice model. This makes it possible to use attitudes as explanatory variables in the choice model. When one expects that the attitudes of the respondents influence choice behavior, it is desirable to estimate a hybrid model (Kim, et al., 2014). The survey should include (attitudinal) statements that the respondent needs to rate, to obtain the attitudes of respondents. By applying the Explanatory Factor Analysis (EFA) on the statements (see section 6.1.2), the latent factors can be identified and included in the hybrid model (Ben-Akiva, 2002; Kim, et al., 2014). The latent variable model and the different discrete choice models can be sequentially estimated. The latent factors from the EFA can be added as average sum scores. In this way, the varying loadings of the attitudes with the factors are ignored. Consequently, the model can only estimate whether attitudes influence the choice of a hydrogen system with an alternative design. Researches can estimate behavior relationships between explanatory factors and attributes by estimating the discrete choice model and the latent factor model simultaneously. However, this exponentially increases the computation time per extra number of factors added (Temme, et al., 2008). The sequential estimation is assumed to be sufficient for exploratory studies (DiStefano, et al., 2009).

It is important to note that there is criticism adding attitudes as latent variables in choice models. When estimating a hybrid model, it is crucial to be aware of this ongoing discussion. The report of Chorus & Kroesen (2018) identifies different problems. Firstly, specific attitudes have a strong correlation with behavior. A causal relation causes this correlation. Specific attitudes will affect behavior, but specific attitudes are also influenced by behavior (Chorus & Kroesen, 2018). The reverse causality is ignored in hybrid models. More research is needed to understand the bidirectional relation between attitude and choice behavior (Chorus & Kroesen, 2018). Another problem identified is that attitudes and perceptions are measured at one point in time (Chorus & Kroesen, 2014). This measurement causes the latent variables only to observe differences between individuals. The variables do not observe the variation within or the changes for the same individual (Chorus & Kroesen, 2014). There is no causal inference at the level of an individual.

Consequently, hybrid models do not support the use of policies that aims to change the attitude (latent variable) to change choice behavior (Chorus & Kroesen, 2014; Chorus & Kroesen, 2018). It is recommended not to make any recommendations that focus on influencing the attitude to increase the support for policies. Limited evidence is around whether these recommendations are effective (Chorus & Kroesen, 2014; Chorus & Kroesen, 2018). In this research, no recommendations must be made that focus on influencing the attitude to change the WTP for the reliability or the willingness to accept a sustainable hydrogen system used for heating with a lower level in reliability and costs.

5. Methodology used for discrete choice modeling

This chapter displays the construction of the survey and the stated choice experiment. First, section 5.1 discusses the attributes and the levels of the attribute included in the stated choice experiment. After that, section 5.2 determines the design of the choice sets of the survey. The design of the survey is based upon literature and is eventually determined by the software tool Ngene. Section 5.3 elaborates on the construction of the questionnaire. Section 5.4 shows the description of the sample, and section 5.5 shortly addresses the privacy and ethics of the research. Finally, section 5.6 shortly touches on the pilot study.

5.1 Selection of attributes and attributes levels

The attributes to include are based on the literature study performed in chapters 2 and 3. The attributes chosen are variables that are assumed to create flexibility on the demand side. The variable can create flexibility on the demand side by either significantly reducing the gas use or the fact that not one preferred setting of the variable exists.

5.1.1 Reliability connected to the outside temperature

The grid operators are obliged to guarantee a certain level of reliability, and the ACM tests this. The ACM will not allow any grid operator to reduce its grid capacity if it causes interruptions in the system. For the selection of the attribute levels, the capacity of the electrolyser must ensure a sufficient level of reliability. The weather data of the KNMI is analyzed to determine reasonable levels of reliability. Because the demand for gas is strongly related to the outside temperature, sufficiently low outside temperatures should be determined until which the electrolyser is obliged to serve all demand. The minimum temperatures over de past 20 years were analyzed. Based on the weather data of the KNMI, it can be concluded that one extreme cold period occurred in February 2012. From 2 February 2012 till 8 February 2012, the maximum temperature measured was -3,6°C, while the minimum temperature measured was -18,8°C (KNMI, n.d.). This period is the only period that surpasses a 24-hours minimum temperature of -5 °C. Therefore, this 24-hours temperature is set as the lowest level at which there should be enough generation capacity at a local level to serve the demand. In the report of Stedin for Stad aan 't Haringvliet there is chosen to create a 24-hours minimum temperature of -7°C as the bound at which the local capacity should be enough to serve the demand (Ekentis, 2020). The minimum of -7°C is set as the middle level. Finally, in the past 20 years, a 24-hour temperature of -9°C is not reached. The capacity needed to locally generate enough energy to serve demand until a 24-hour temperature of -9°C is set as the upper bound in this research.

5.1.2 Cost reduction obtained from a lower level of reliability

Chapter 2 identifies the importance of economic incentives when there is a desire to influence demand and create demand flexibility. Even more, since the design of a reliable system used for heating comes with certain costs, it is essential to look for the optimum between the cost and reliability from the perspective of households.

Most people have a negative association with the cost. Therefore, the term possible *cost reduction* is included in the stated choice experiment. The levels of cost reduction given are based upon the difference in investment cost between electrolysers (see subsection 3.2.1).

Section 3.2.1 showed that the construction cost of an electrolyser serving demand till -12°C would cost around €16 million, while an electrolyser serving demand -7°C would cost approximately €13,8 million. In the same way, the construction cost of the electrolysers serving demand till -9°C and -5°C can be determined, namely respectively ±€14,8 million and ±€12,8 million. The difference in investment cost determines the cost reductions obtained by lowering the generation capacity, and the level of reliability. Table 5.1 shows the cost reduction by lowering the generation capacity.

Table 5.1 – Cost reduction from the lower capacity electrolyser

Minimal 24-hour temperature	Construction costs	Cost reduction
-12°C	± €16.000.000	0%
-9°C	± €14.800.000	7,5%
-7°C	± €13.800.000	14,7%
-5°C	± €12.800.000	20%

For simplicity reasons, this report assumes that the hydrogen system delivering according to the current regulations (delivering till -12°C), will have the same average energy bill as in the current natural gas system. The average gas bill is €1.035 per year (Milieu Centraal, 2020). The obtained cost reduction is obtained by multiplying the cost reduction (in percentage) with the average energy bill of €1.035. In reality, the energy bill will increase by the use of green hydrogen instead of natural gas. However, the cost reduction obtained by lowering the reliability will then be even more considerable.

This research considers the following cost reductions (the multiplications are rounded up):
-9°C implies a cost reduction of €80 per year;
-7°C implies a cost reduction of €145 per year;
-5°C implies a cost reduction of €210 per year.

These cost reductions are based upon the current cost of building an electrolyser. The construction costs will significantly reduce in the coming years, but calculating the construction cost based on the expectations for 2030 results in the same proportions of cost reduction. The calculated cost reductions for 2030 fall in the range identified for 2020. Appendix A shows these calculations. Therefore, the states choice experiment will use the cost reductions of €80, €145, and €210 per year

5.1.3 Reducing demand by a maximum indoor temperature

The primary purpose of the gas used in the residential sectors is space heating. The goal of space heating is to keep houses and rooms thermally comfortable. The thermal temperature inside a big driver to increase the demand for gas. It is possible to use the temperature indoor as the parameter of thermal comfort. Furthermore, the reduction of the indoor temperature by 1°C will lower the gas demand by 6%. The willingness to reduce the level of reliability by lowering the indoor temperature is measured when this attribute is included in the stated choice experiment.

The average temperature indoor depends on the preferences of the household, and the literature identifies different indications for the preferred indoor temperature. Yohanis & Mandol indicated that a minimum comfortable indoor temperature is 16°C, while Santamouris, et al. (2014) and Schellen, et al. (2010) state a minimal comfortable temperature of 17°C. Based on the pilot study, this report found that an indoor temperature of 16°C was too cold. Therefore, this report chooses to use a minimal temperature of 17°C.

The highest recommended indoor temperature indicated is 21°C. However, the highest maintained indoor temperature is indicated at 23°C (Conner & Lucas, 1990; Yohanis & Mandol, 2010). This thesis uses the highest recommended temperature as the upper level of this attribute. The indicated average indoor temperature is between 19-20°C. The middle level of the attribute is set at 19°C to create linearity.

5.1.4 Reducing demand by a maximum amount of rooms heated

Literature states that the temperature varies significantly between rooms in a house. There is a correlation between the occupancy of the room and the temperature. A more occupied room generally has a higher temperature than rooms that are less occupied. Furthermore, a household can achieve an energy reduction of 15% if a household only heats the room that is occupied. Therefore, this attribute may be a possible way to create demand flexibility.

The upper level indicated for this attribute will be all the rooms in the house. The lowest level will be one room in the house. On average, a household in the Netherlands contains 2,1 people. Assuming that every person in a household wants to be in one room, the last attribute level included in the stated choice experiment is heating three rooms.

5.1.5 Reducing demand for a maximum amount of hours per year

The outside temperature influences the demand for gas. The influence implies that demand reductions are only necessary during hours with an extremely low outside temperature. During these hours, the demand for gas is the highest. As indicated above, the reliability levels at which the electrolyser should deliver hydrogen are -5°C, -7°C, and -9°C. The demand for hydrogen must decrease if the outside temperature exceeds these levels to ensure a match between supply and demand. To create some sort of buffer in the system, in case the temperature will drop or the cold period will take very long, this report chooses to analyze the moments when in the last 20 years, a minimum of respectively -5°C, -7°C, or -9°C occurs for more than 4 hours. Dividing this amount with 20 years results in the number of hours per year that longer than 4 hours the temperatures are reached. Table 5.2 shows these numbers. These numbers are rounded up.

Table 5.2 - Indication of the number of hours with demand constraints

Temperature	**# time longer than 4 hours in 20 years**	**# per year**
-5°C	570 times	29 hours/year
-7°C	196 times	10 hours/year
-9°C	46 times	3 hours/year

5.1.6 Identification of attributes and attribute levels

Table 5.3 shows all the attributes and attribute levels included in this research.

Table 5.3 - Attributes and attribute levels

Attributes			
Cost reduction	€80/year	€145/year	€210/year
Amount of hours per year	3 hours/year	10 hours/year	29 hours/year
Maximum of indoor temperature	17°C	19°C	21°C
The maximum amount of rooms heated	One room	Three rooms	All rooms

5.2 Experimental design

The different alternatives are based on the attributes and the attribute levels determined in section 5.1. Every choice set contains two hydrogen alternatives and the natural gas alternative. In the natural gas alternative, nothing will change compared to the current situation. In this alternative, there is no cost reduction. Furthermore, households can always maintain the preferred indoor temperature in all rooms. By including the natural gas alternative, the respondent is not forced to choose an alternative hydrogen design with a lower level of reliability.

There are different ways to set up the stated choice experiment. For the design, one can either choose a full or a fractional factorial design. A full factorial design constructs all possible combinations of the attribute levels. This research chooses a fractional factorial design since a full factorial design will lead to too many choice sets, namely 243 choice sets (Molin, 2018; Walker, et al., 2018). A fractional factorial design creates the possibility to reduce the number of alternatives. There are three ways to set up a fractional factorial design: a random design, an orthogonal design, and an efficient design. This research chooses an orthogonal design over a random design. In a random design, a fraction of the full factorial design is selected randomly. Therefore, there will be correlations between the attributes. Consequently, higher standard errors of the parameters exist, which leads to less reliable parameters (Molin, 2018).

The most common design for stated choice experiments is an orthogonal design. Within orthogonal designs, the attributes included in the design are uncorrelated and have attribute level balance (all the levels are equally distributed) (Walker, et al., 2018). A downside of orthogonal designs is the existence of dominant alternatives. Dominant alternatives are alternatives that are at least better on one attribute and are not worse on all other attributes (Molin, 2018). These alternatives do not provide any information about the trade-off of respondents. Dominant alternatives should be removed from the experiment. By removing the dominant alternatives, there will be no attribute level balance. Therefore, the main advantage of no correlations between attributes of an orthogonal design will no longer exist (Molin, 2018).

Efficient designs can reduce the problem of dominant alternatives. Efficient designs aim to balance the utilities in all the choice sets in a way to avoid dominance. Efficient designs maximize the information about the trade-offs and minimizes the standard errors of the parameters (Molin, 2018). However, to create efficient designs, priors are needed. Priors are the best guess for the parameter values. It is crucial to estimate "good" priors. Good priors will significantly increase the efficiency of the design, while wrong priors decrease the efficiency of the design and lead to biased parameters (Walker, et al., 2018).

The most commonly used techniques for estimating priors is by using literature or by performing a pilot study (Molin, 2018). This research is not able to determine priors based upon a literature study since no similar research has been performed. Due to time constraints, a pilot study does not seem an appropriate solution as well. Within this research, the exact magnitude of the parameters are unknown, while the direction of the parameters can be reasoned as follows:

- *Cost reduction:* By increasing the amount of discount, the respondent is more likely to choose the alternative. Therefore, this attribute has a positive sign.

- *Time:* By increasing the number of hours per year, the alternative will be less appealing and less chosen. This attribute has a negative sign.

- *Indoor temperature:* By lowering the indoor temperature, the level of comfort will reduce. Therefore, the alternative with a higher indoor temperature is more attractive. This attribute will have a positive sign.

- *Rooms:* The alternative with more rooms heated will be more desirable. This attribute is dummy-coded, and the reference value is all rooms. Therefore, this attribute has a negative sign, since fewer rooms heated will make the alternative less appealing.

Bliemer & Collins (2016) presented another way of estimating priors that lead to an optimal design if little information about priors is known. They indicated that with little knowledge about priors, an optimal design could be created by setting the prior means in such a way that each attribute equally contributes to the utility. There is made use of a Bayesian efficient design. The research identified the sign of the priors. The magnitude of the priors for the continuous attributes is set equal to plus or minus one divided by the range of the attribute levels. The priors of the dummy coded variable equals plus or minus 0,5 for each variable that is dummy coded. The standard deviation of the Bayesian prior is half of the calculated prior (Bliemer & Collins, 2016).

The software package Ngene was used to create the Bayesian efficient design. For this design, 12 choice sets were constructed. The number of estimated parameters and the information obtained from each choice determines the number of choice sets (Molin, 2018). In this stated choice experiment, four parameters are estimated. Every choice set contains three alternatives. The parameters and alternatives included result in four plus two degrees of freedom. Therefore, a minimum of six choice sets needs to be constructed.

This research will construct more choice sets to test for linearity and interaction effects. It is known that many choice sets shown to the respondents will be too exhausting for the respondents. This research constructs 12 choice sets to preserve attribute level balance and to be able to create two equally sized versions, each with six choice sets. A blocking column was used to create these two versions. The column assigned the choice sets to the blocks. Appendix D shows the experimental design obtained from Ngene, together with the syntax used. Every choice set consists of two hydrogen alternatives and one natural gas alternative. The natural gas alternative will be the same in every choice set. The levels of the natural gas alternative are not incorporated in the design of the choice experiment.

5.3 Questionnaire construction

After the stated choice experiment, a questionnaire is added. The questionnaire is added to gather the socio-demographic and economic variables, the heating habits and housing characteristics, and the attitude towards hydrogen and sustainable heating. The questionnaire consists of two parts. First, different statements are added to discover the opinion and attitudes of the respondent towards green hydrogen. The Likert Scale is used. Sub-section 5.3.1 further elaborates on this of the questionnaire. Section 5.3.2 shows the last part of the survey. The last part of the survey consists of questions related to different characteristics of the respondents. Appendix E shows the questions and statements added to the survey.

5.3.1 Include attitudes towards hydrogen

The second part of the survey aims to determine the attitude of the respondent towards sustainable hydrogen. It would be interesting to find out whether a respondent with a positive attitude towards sustainable heating and/or hydrogen also has a preference for reducing the level of reliability in the system used for heating (see section 2.4). The respondent rate to what extent he or she agrees with different statements, displayed on a 7-point Likert Scale in the range from “Completely disagree” to “Completely agree.” A 7-point Likert Scale is chosen to increase the probability that the real objective of the respondent is met (Joshi, et al., 2015). There is much criticism on the use of attitudes. In this research, attitudes will only be used as explanatory factors. They will help determine whether front runners on sustainability see a reduction of reliability as desired and probably as a precondition to start the energy transition in the built environment.

5.3.2 Include socio-demographic variables, heating habits, and house characteristics

The final part of the survey contains some socio-demographic and economic questions and some questions that try to find out the heating habits and housing characteristics of the respondents. The answers will be used to determine the influence on the Willingness To Pay (WTP) for reliability in energy systems or the preference for an alternative hydrogen design with a lower level of cost and reliability. The questions are based on the factors identified in section 2.4. Appendix E shows the complete survey.

5.4 Sample selection

The respondents of this research are 18 years and older and are living in the Netherlands. The aim is to find a representative sample of the population to fill in the survey. The goal is to determine whether the households prefer a lower level of reliability in exchange for money. Moreover, this research intends to find the average WTP for reliability. A representative opinion of the households is desired. Therefore, a representative group is needed. Moreover much response is preferred to create a general opinion about this subject. The respondents are found by using the network of Stedin.

5.5 Privacy and ethics

In May 2018, the General Data Protection Regulation (GDPR) became applicable in Europe. This research does not like the answers to individuals, and the survey does not request data that make the respondent traceable. All the respondents will remain anonymous. Therefore, this research is in line with the minimal data processing principle of the GDPR. The introduction of the survey informs the respondents that when filling in the survey, their data will be stored and used for scientific research. Lastly, to sensitive questions (for example related to income), the additional answer ”prefer not to answer” was added.

5.6 Pilot study

Before conducting the final survey, a pilot study is performed to improve the survey based on the feedback of respondents. The pilot study also tested the different attribute levels. To test the clarity of the survey before sending it out to the complete sample can be done most appropriately by asking respondents that are not familiar with the subject. Therefore, a group that was not well-known with the subject was asked to fill in the survey. Appendix C shows the feedback from the pilot study.

6. Sample description

This chapter analyses the descriptive results of the stated choice experiment. It will identify the preferences of the households related to the design of a hydrogen infrastructure and the Willingness To Pay (WTP) of the households for a reliable energy system. Section 6.1 discusses the data collection method and data preparation. Afterward, section 6.2 evaluates the collected data. This section includes the sample characteristics and their representative, the choice behavior of the respondents, and the assessment of non-trading behavior.

6.1 Data collection and preparation

This research collected the data by the Qualtrics survey software. The data is gathered between the 14th of July until the 17th of August 2020. Everyone living in the Netherlands and older than 18 years old was allowed to fill in the survey.

In total, 510 respondents started the survey, while 411 respondents completed the whole survey. Thus, 18,6% of the respondents dropped out of the survey. The recruitment of the respondents is done in different ways. First, a link to the survey is posted at the end of the online customer satisfaction survey of Stedin. Second, the employees of Stedin were recruited by the use of the online platform of Stedin. Third, the researcher used social media such as Facebook and Linked-in. Finally, the snowball method was used to recruit more respondents. The employees of Stedin and respondents reached by the use of social media channels were asked to distribute the survey among their connections.

Section 5.2 described the blocking used to divide the 12 choice sets into two blocks, each consisting of six choice sets. Each respondent was shown one block of 6 choice sets. In total, 323 respondents (79%) completed the survey with the choice sets of block 1, while 88 respondents (21%) completed the survey consisting of the choice sets of block 2. One can see that more respondents filled in the survey consisting of the choice sets of block one. However, the number of respondents for both blocks outreaches the minimal amount of respondents needed (n=31) to say something about the results. Concludingly, this is not seen as a severe problem.

After the data collection, the data must be prepared for data analysis. First, the data is cleaned. Appendix F shows the steps taken to clean the data. Sub-section 6.1.1 determines the coding of the estimated choices. Sub-section 6.1.2 performs the Explanatory Factor Analysis (EFA) on the statements added in the second part of the questionnaire.

6.1.1 Coding of variables

Variables need to be coded to estimate the choice models—table 6.1 displays the coding of the variables. From the attributes, only the amount of rooms is a nominal variable. For this variable, dummy coding was applied, and "all rooms" is the reference category (Molin, 2018). The reference level has a utility of zero. The utility contribution of the other levels is the difference in utility compared to the reference level, so compared to "all rooms" (Molin, 2018).

The socio-demographic and economic variables and the heating habits and housing characteristics are effect coded since no clear base-level exists for these variables. By applying effect coding, the average utility contribution is set to zero. The utility contribution of a certain level displays the difference with the average utility contribution (Molin, 2018).

This research considers the level of income and education as interval variables. One can note that this is not entirely correct, since the distance between the levels cannot always be considered equal. The alternative would be to estimate these variables as dummy variables. A major downside would be that the statistical power would decrease due to the increase in estimated variables. A decrease in statistical power increases the probability that a coefficient is wrongly assumed as not significant. Therefore, this research assumes that the level of income and education are interval variables.

Table 6.3 - Coding of variables

Variable	**Level**	**Coding**			
Amount of rooms heated	One room (0)	1		0	
	Three rooms (1)	0		1	
	All rooms (2)	0		0	
Gender	Men	1			
	Women	-1			
Age	18 – 25 years old	-1	-1	-1	-1
	26 – 45 years old	0	0	0	1
	46 - 65 years old	0	0	1	0
	66 – 80 years old	0	1	0	0
	80+ - years old	1	0	0	0
Income	Less than €10.000 per year	0			
	€10.000 - €20.000 per year	1			
	€20.000 - €30.000 per year	2			
	€30.000 - €40.000 per year	3			
	€40.000 - €50.000 per year	4			
	€50.000 - €60.000 per year	5			
	€60.000 - €70.000 per year	6			
	€70.000 - €80.000 per year	7			
	€80.000 - €90.000 per year	8			
	€90.000 - €100.000 per year	9			
	More than €100.000 per year	10			
Education	Primary school	0			
	High school	1			
	Secondary vocational education (MBO)	2			
	Higher professional education (HBO)	3			
	Academic education (WO)	4			
Insulation	Limited measures are taken - Not aware which - One measure taken	1		0	
	Some measures are taken - Two-three measures taken	0		1	
	Many measures taken - Four-five measures	-1		-1	
Size household	One person	0			
	Two persons	1			
	Three persons	2			
	Four persons	3			
	Five or more persons	4			
Homeowner	Owner of house	1			
	Rent a house	-1			
City or village	City (>25.000 inhabitants)	1			
	Village (<25.000 inhabitants)	-1			

Connection gas grid	Yes	1	
	No	-1	
Insights in gas usage	Yes	1	
	No	-1	
Time at home	Almost always	1	0
	Generally - During the morning, evening, night, and weekend - During the weekend	0	1
	Rarely - (Almost) never - During morning, evening, and night	-1	-1
Indoor temperature day	Colder than 16℃	0	
	16 – 17 ℃	1	
	17 - 18℃	2	
	18 - 19℃	3	
	19 - 20℃	4	
	20 - 21℃	5	
	21 - 22℃	6	
	22 - 23℃	7	
	Warmer than 23℃	8	
Indoor temperature night	Colder than 16℃	0	
	16 – 17 ℃	1	
	17 - 18℃	2	
	18 - 19℃	3	
	19 - 20℃	4	
	20 - 21℃	5	
	21 - 22℃	6	
	22 - 23℃	7	
	Warmer than 23℃	8	
Save energy	No	1	0
	Few measures are taken - Two-four measures	0	1
	A lot of measures taken - More than four measures	-1	-1
Shower	Yes	1	0
	Yes, but - Only when convenient - Not during the weekend	0	1
	Nee	-1	-1
Building year house	Older than 1920	0	
	Between 1920 - 1930	1	
	Between 1930 – 1940	2	
	Between 1940 – 1950	3	
	Between 1950 – 1960	4	
	Between 1960 – 1970	5	
	Between 1970 – 1980	6	
	Between 1980 – 1990	7	
	Older than 1990	8	

6.1.2 Exploratory Factor Analysis

The attitude of the households towards hydrogen and sustainable heating is an essential factor for the effective out roll of a hydrogen system. Currently, households are connected to the natural gas infrastructure and cannot be forced to change their heating fuel. If one household decides to keep the natural gas connection, Stedin is forced to keep the natural gas infrastructure. Stedin needs to provide the household with natural gas, while the other houses in the neighborhood will be connected to a different infrastructure. It is desirable to create a threshold value for the minimal amount of households in a neighborhood that wants to use hydrogen. It is costly if Stedin has to maintain and lay down two infrastructures next to each other. However, even with the threshold value, the positive attitudes towards hydrogen and the disconnection of natural gas are essential.

It is crucial to map the attitudes towards hydrogen when considering the preference related to an affordable and reliable hydrogen system. Moreover, this research expects that the attitudes and beliefs of respondents influence the choice of a hydrogen system with a lower level of reliability. Respondents with a more positive attitude towards hydrogen will have a higher preference for using a hydrogen system with a lower level of reliability. Furthermore, this group will probably have a lower WTP for reliability since they may see the reduced level of reliability as a precondition to implement a hydrogen infrastructure.

The second part of the survey showed different statements to the respondents to identify the attitudes of the households. The respondents needed to rate these statements on a 7-point Likert scale. These ratings are used as input for the exploratory factor analysis (EFA). This research uses EFA since there are no restrictions related to the number of extracted factors. Moreover, there are no restrictions on the particular relationship patterns between the variables. If the restrictions are applicable, the Conformatory Factor Analysis (CFA) should be used (Fabrigar, et al. 1999). The EFA tests the correlation between statements to investigate whether a collection of variables have an underlying factor. By using the EFA, the number of variables can be reduced, and the underlying latent variables can be identified. The hybrid choice model will use the latent variables (Williamson, et al. 2010).

For the execution of the EFA, the method of factor extraction should be determined. The two most commonly used methods are the Principal Component Analysis (PCA) or Principal Axis Factoring (PAF). The PCA is a mathematical technique to summarize the variables into fewer dimensions and maintaining as much variance as possible. PAF focusses on the common variance between the variables and is used to measure latent variables (Molin, 2019). This study performs the factor extraction by PAF.

This study uses SPSS to identify the underlying factors. To investigate whether the data is suitable for a factor analyze, the Barlett's test of sphericity and the Kaiser-Meyer-Olkin (KMO) test is performed. The KMO test is 0,820 (which is greater than 0,5), and the Barlett's test of sphericity is significant, see Appendix G. Based on these tests, the data is considered suitable for the Exploratory Factor Analysis (Williamson, et al. 2010).

Different rules exist for the number of factors extracted by the EFA. General rules are Kaiser's criteria and the scree test (Williamson, et al.). The Kaiser criteria state that a factor with an eigenvalue greater than one should be considered (Kaiser, 1960). The scree plot displays the eigenvalues of the initial components. Based on the scree-test, one must analyze at which component the line of the scree plot flattens. This component and all the remaining components will be left out of the analysis (Williamson, et al. 2010). Appendix G shows the complete analysis. Based on the Kaiser's criteria and the scree test (see Appendix G), this study uses three factors for the EFA.

When performing the EFA, skewed rotation is used (with a delta of -7). Skewed rotation instead of orthogonal rotation is used because orthogonal rotation did not lead to a simple structure at which the variables load high on one factor and low on the others. Using skewed rotation implies that the meaning of the factors overlaps since the factors will correlate (no orthogonality is enforced). Consequently, the factors have something in common (they correlate). The commonality between the factors must be considered when the factors are named. Lastly, the factor loads lower than 0.30 are excluded from the estimation. Table 6.2 shows the estimation results of the Explanatory Factor Analysis.

Table 6.4 - Factor Exploratory Analysis

	Factor 1	**Factor 2**	**Factor 3**
ST1: Sustainability important	0,623		
ST2: Willing to cut-off natural gas	0,889		
ST3: Willing to heat with hydrogen	0,718	0,320	
ST4: Willing to heat with electricity	0,790		
ST5: Willing to heat with green gas	0,470		
ST6: Willing to use a heating system	0,672		
ST7: Expectation hydrogen is safe		0,719	
ST8: Expectation hydrogen is expensive			0,394
ST9: Expectation hydrogen is reliable		0,700	
ST10: Expectation hydrogen 100% CO2 reduction		0,393	
ST11: Renovation should be in a short time			0,476

Table 6.2 shows that one variable (willingness to heat their house by sustainable hydrogen) has loadings on two different factors, Factor 1 and Factor 2. The loading on Factor 1 is high, while the loading on Factor 2 is low. It is undesirable if a variable load on two factors. However, since the loading on one factor is high, and on the other low, this report assumes that the loading will not cause any problems. In this way, the report can maintain a simple structure (Molin, 2019).

The outcome of the EFA is a three-factor solution. One must keep in mind that the factors correlated due to the skewed rotation. The correlation should be kept in mind when interpreting the factors. The interpretation of the factors needs to show some overlap. The first factor includes variables that concern the willingness to use sustainable energy sources for heating. Therefore, the first factor will be *The expectation to use sustainable heating.* The second variable contains variables concerned with the expectation of hydrogen. The second variable will be *The expectation of hydrogen*. The third and last factor includes whether the respondents expect that hydrogen is expensive and whether renovation should be in a short period. The name of the third variable is *The expectation of time and money.*

6.2 Descriptive analysis

This section will briefly analyze the data gathered from the stated choice experiment. First, sub-section 6.2.1 analyzes if the sample is representative of the Dutch population. After that, the implications of an unrepresentative sample are discussed. Section 6.2.2 discusses the choices in the stated choice experiment made by the respondents. Section 6.2.3 identifies the non-trading behavior of the respondents and its' implications.

6.2.1 Representativity of the sample and its implications

This sub-section performs statistical tests to test whether the sample is representative of the Dutch population. The tests are done based on gender, age, education, and income. Appendix H show the tests and the results of the tests. The report compared the sample to the entire population of The Netherlands. Based on these tests, one can conclude that the sample is unrepresentative for the Dutch population regarding gender, age, educational level, and income. Males are highly overrepresented, and females are underrepresented. The age groups of 56 – 65 and 66 – 80 years old are overrepresented, while the other groups are underrepresented. The high level of education is overrepresented in the sample compared to the population, whereas the middle and low education levels are underrepresented. Finally, the higher income levels of the sample are highly overrepresented, whereas the low-income levels are highly underrepresented compared to the actual income of the population.

Based on the comparison between the sample and the population, one can conclude that the sample is biased regarding gender, age, education level, and income. The unrepresentative sample might result in biased parameters. It can be expected that the overrepresented group with a high income are less sensitive for cost reduction since this group is less constrained by their income. Furthermore, it should be kept in mind that in general, older households are less willing to change their energy sources to sustainable alternatives or alternatives with another level of reliability. Consequently, the parameter estimate for the change to a sustainable hydrogen system might be underestimated due to the overrepresented group of respondents in the age categories of 56 – 65 years old and 66 - 80 years old.

Furthermore, due to self-selection, other biases may have occurred as well. Respondents were asked voluntarily to fill in the survey. Therefore, it is likely that respondents with a stronger opinion about the design of the hydrogen system filled in the survey more often than respondents with a less strong opinion. Moreover, this researched used web surveys, which are sensitive to self-selection. The respondents select themselves. Moreover, only respondents with internet will be covered (Bethlehem, 2010). When analyzing and interpreting the results, it is essential to keep in mind the biases, since these might influence the results.

6.2.2 Choice behavior of respondents

The survey presented to the respondent started with six choice sets, each consisting of 3 choice options. The first two choice options consisted of a sustainable hydrogen system, varying in their cost and reliability. The last choice option was the current natural gas system. In total, the respondents voted 1732 times in favor of introducing a sustainable hydrogen system with a lower level of the cost and the reliability, while 734 times the respondents voted in favor of the natural gas system. Thus, 70% of the choices were in favor of the sustainable hydrogen system. More than two-thirds of the total amount of choices were in favor of a hydrogen system with a different level of reliability.

Figure 6.1 shows the distribution of the choices per choice. This graph shows that for every choice set more than half of the sample favors the sustainable hydrogen grid with a different design concerning the cost and the reliability. Furthermore, 224 of the respondents always choose in favor of the sustainable hydrogen system, which equals 55%. More than half of the respondents always choose a hydrogen system with a lower level of reliability and cost. The next sub-section analyzes the respondents that always voted in for the same alternative.

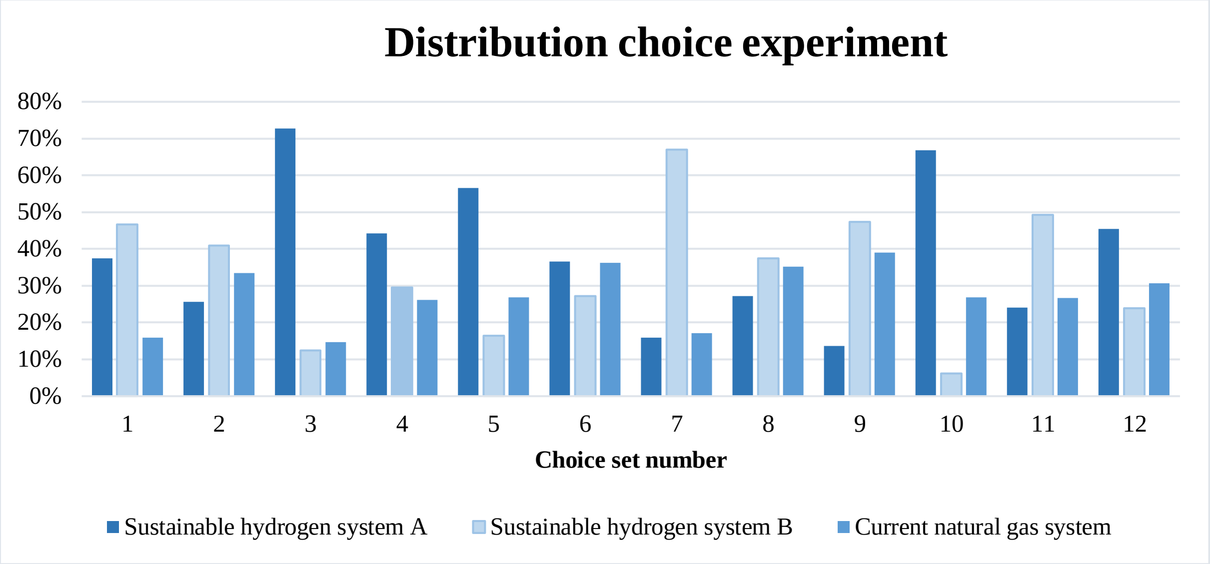

Figure 6.1 - Distribution choice experiment

6.2.3 Non-trading analysis

In this research, it is the case that several respondents always choose the same alternative in every choice set, which is called non-trading behavior. Non-trading behavior mostly occurs in choice experiments with labeled alternatives, such as in this research. Hess, et al. (2010) identifies three different ways non-trading behavior occurs.

Firstly, the respondent does not understand the survey, takes the survey not seriously, or gets bored or fatigue when filling it in. Secondly, the respondent might choose strategically or politically. Thirdly, the respondent might have an extreme preference for maintaining the current situation (Hess, et al. 2010). The extreme preference for maintaining the current situation can be due to a very negative attitude towards hydrogen or a strong preference for a very reliable system used for heating. Distinguishing the causes for the non-trading behavior is nearly impossible. The non-trading behavior will influence the alternative specific constants and inertia terms. The non-trading behavior might also have some impact on the Willingness To Pay (WTP) indicators and the marginal utility coefficients. It might also bias the estimates of important coefficients (Hess, et al. 2010).

This research performs a non-trading analysis to analyze whether the respondents always choose the current natural gas system or the same sustainable hydrogen system. The complete choice set data contains 411 respondents, of which 20% showed non-trading behavior. These respondents either choose six times the current natural gas grid or always for the first or the second sustainable hydrogen grid. In total, 78 respondents (93% of the non-traders) always choose to maintain the current natural gas system. Six of the respondents (7% of the non-traders) always voted for the same sustainable hydrogen alternative. The remaining 80% of the respondents voted differently per choice set, depending on the design of the sustainable hydrogen grid.

There is the possibility that the non-trading behavior wrongly influences the WTP indicators and the utility coefficients (Hess, et al., 2010). However, to determine the average WTP for reliability and determine whether the population prefers a system used for heating with a lower level of reliability and cost, it is crucial to incorporate the households that have a preference for maintaining the current situation. This includes the households that always choose to maintain the current situation, caused by the fact that they have a strong preference for maintaining the current situation. There are several reasons for respondents to choose always the base alternative, which have nothing to do with non-trading behavior (Ahlheim & Neidhardt, 2010).

It is unknown what the real incentives were for the respondents always to choose the natural gas system. This report expects that the non-traders, that always choose to maintain the current situation will give insights into the average WTP since most of these respondents presumably prefer maintaining the current situation. Moreover, the decision to choose always the base alternative has different explanations that have nothing in common with non-trading behavior. Therefore, the removal of data where respondents always choose the natural gas alternative is problematic (Ahlheim & Neidhardt, 2010). This research chooses to keep the complete data set for the parameter estimation and take the non-trading behavior caused by boredom or strategical motive for granted. However, it is important to keep in mind the non-trading behavior incentives when concluding.

Furthermore, six respondents always choose the same sustainable hydrogen alternative. The drivers for this group of non-traders are not known. However, since 6 out of 411 is only 1%, it is assumed that this will not have severe implications for the parameter estimates and the WTP estimates.

The gathered sample is unrepresentative of socio-demographic characteristics, and the specification of non-trading behavior on these characteristics is not seen as an additional value. For example, the percentage of men showing non-trading behavior will give a distorted view. Since many more males filled in the survey, the percentage of males showing non-trading behavior will automatically be higher than females. No useful conclusions can be drawn from this.

7. Discussion of different choice models

Within this chapter, the different choice models presented in subsection 4.2.1 are discussed and compared. It is essential to make a deliberate decision when determining the choice model used to estimate the preferences of the households related to the trade-off between the reliability and affordability of a hydrogen system. Every choice model has its' own advantages and disadvantages. It is essential to consider those to minimize the chance of biased parameter estimates.

This thesis searches for the probability that the sustainable hydrogen grid with a lower level in reliability and cost is chosen over the current natural gas grid. An assumption about the probability distribution of the random utility ε is needed to determine the choice probability (Keane, 1997; Koppelman & Bhat, 2006). This chapter discusses three models with different assumptions and determines which model to use in this research.

The data used as input for the choice models consists of 2466 choices, and all the choice models are estimated using Python Biogeme. In the stated choice experiment, the respondents needed to choose between three alternatives. One of these alternatives is the base alternative. The base alternative is the natural gas system, in which the cost and the level of reliability remain the same. Comparing the choices of all three alternatives gives more information about the trade-off between a reliable and affordable hydrogen system, which will lead to more reliable parameter estimates. Therefore, the utility functions of all three alternatives are used to determine the parameter estimates. Chapter 5 discusses the levels of the attributes per choice set for hydrogen alternatives. The levels of the different attributes of the natural gas alternative are the same in every choice set. There is no cost reduction, and there is no time at which there are demand constraints. Households can heat all the rooms at a maximum indoor temperature of 23℃. A maximum temperature of 23℃ is chosen because only one respondent indicated maintaining an indoor temperature above 23℃. An alternative specific constant is added to both the systematic utility functions of the hydrogen alternatives. This constant displays the mean like or dislike for a hydrogen system with a lower level of reliability and cost.

This chapter aims to determine the choice model used to answer the research question. Section 7.1 discusses three choice models that are analyzed in this research. Section 7.2 specifies and estimates the first model. This model is the multinomial logit (MNL) model and is popular due to its simplicity. After that, section 7.3 will analyze the mixed logit (ML) model. The ML model corrects for certain assumptions made in the MNL model. The next section will further explain these assumptions. After that, section 7.4 compares the estimations of both models. Finally, section 7.5 displays the final model estimations interpreted in the next chapter.

7.1 Explanation to estimate different choice models

The most used choice model is the multinomial logit (MNL). This model is mainly popular due to its simplicity and elegance. Moreover, the estimation of this model is not time-consuming. The next section shows the result of this model.

A main drawback of the MNL is due to its simplicity, namely by the i.i.d. error term assumption (for the explanation, see subsection 4.2.1). Wrongly assuming that the i.i.d. error term assumption holds can lead to biased parameter estimates. The i.i.d. assumption does not hold when the following statements are true (Chorus, 2019):

1. One or more subsets of the alternatives in the choice set have common factors;
2. The utility associated with these common factors varies across individuals;
3. The variation in utility is not fully captured in the systematic utility function "V."

In the stated choice experiment, the two hydrogen alternatives share common factors. In both alternatives, hydrogen is used as heating fuel. Moreover, both alternatives display a system with a lower level of reliability and cost reduction. Both arguments imply that the first statement is true. Households obtain a different benefit from a certain level of reliability and cost. Also, the benefit obtained from a sustainable hydrogen alternative varies across households. Therefore, it is expected that the utility associated with the common factors varies between households (the second statement). It is reasonable to assume that not all variables are included in the stated choice experiment that households consider when choosing between heating alternatives. Furthermore, the stated choice experiment contains no variables that consider the common factors of a sustainable hydrogen alternative. Concludingly, the third statement is true. Given that all statements are true, the MNL model wrongly assumes that the IID assumption holds. A Mixed Logit (ML) model should be estimated to overcome biased parameter estimates.

Finally, a hybrid choice model will be estimated to incorporate the attitudes of households into the choice model. The incorporation of attitudes will have additional value for Stedin and will increase the explanatory power of the model. Grid operators such as Stedin are not allowed to force households to change their heating fuel. For the effective implementation of a hydrogen system, households must be willing to change their heating connection. Therefore, it is likely that the households in the first neighbourhoods heated by hydrogen instead of natural gas have a positive attitude towards hydrogen and sustainable heating.

In the coming years, Stedin, and the other grid operators must construct a hydrogen system to transport hydrogen to the households. There is not yet a national grid to alleviate the shortages on a local level. The high level of reliability is created by increasing the generator capacity of electrolysers, through which high upfront investments are needed. The predefined level of reliability determines investment costs. The high upfront investment costs are a barrier, especially in the starting phase. The households living in the first hydrogen neighbourhoods are likely optimistic about hydrogen and sustainable heating. The hypothesis is that this group is the “frontrunner” of the hydrogen infrastructure and will be less concerned about lowering the level of reliability since they can see this as a precondition to rollout a hydrogen system. When creating insights into their preferences related to the trade-off between the reliability and affordability of hydrogen might lead to different recommendations for the first hydrogen projects.

As mentioned in subsection 4.2.1, it is essential to be aware of the ongoing discussion of the usage of hybrid choice models. Furthermore, the estimation of the mean preference for a hydrogen system with a lower level of reliability becomes more difficult due to the usage of hybrid choice models. This research chooses to incorporate the attitudes in the model estimation, caused by the expected additional value for Stedin and the increase in explanatory power. No policy recommendations should be given about influencing the attitudes to change the preferences of the households. Finally, to give insights into the mean preference for a hydrogen system with a lower level of reliability, a model is estimated without the attitudes.

7.2 Multinomial Logit (MNL) model

This section discusses the MNL. The estimation of an MNL model is not very time consuming and helps determine the Mixed Logit (ML) model. First, a base MNL model is estimated that only contains the parameters of the choice experiment. Based on this model, the continuous attributes are tested for linearity. In this research, cost reduction, time, and temperature are continuous attributes. A non-linearity test is performed on these attributes. In a non-linearity test, a quadratic component is added to the continuous attributes in the utility functions of the three alternatives. A statistically significant quadratic component implies that the effect of the attribute is non-linear. In this research, all the estimated quadratic components of the continuous attributes are not significant and are assumed to be linear. Appendix I shows the utility functions of the base MNL model and the base MNL model with quadratic components.

Besides the test for non-linearity, the interaction effects are estimated between the reliability attributes (“time with constraints,” “maximum indoor temperature,” and the “amount of rooms heated”) and the cost reduction attribute in the base MNL model. The expectation is that there is an interaction between the cost reduction and the reliability attributes, namely that more cost reduction would lead to higher acceptability of the reduction in reliability. A higher cost reduction gives a higher utility to the same maximum indoor temperature, the same amount of rooms heated, and the same period with constraint. For example, this report expects that a maximum indoor temperature of 19°C is more preferred when there is a cost reduction of €210 per year compared to €80 per year.

Also, the interaction effects between the time constraint and the maximum temperature, and the number of rooms are estimated. The expectation is that a more extended period with time constraints results in a lower utility for the same maximum indoor temperature and the same amount of rooms heated. For example, a maximum indoor temperature of 19°C has a higher utility if this is only for 3 hours instead of 29 hours per year.

After estimating the interactions, it became apparent that all the interactions between the attributes were insignificant. This research leaves out these interactions. Table 7.2 display the parameter estimates of the base MNL model.

After the estimation of the base MNL model, an extended MNL model is estimated. This model includes the socio-demographic and economic variables, heating habits and housing characteristics, and the latent variables of the attitudes estimated in subsection 6.1.2. The added factors in the extended MNL model are explanatory factors. By adding these factors, it is analyzed whether the factors identified in section 2.4 significantly influence the Willingness To Pay (WTP) for the reliability or the choice for a hydrogen system with a different level of reliability. Section 2.4 identifies the expected effects, while Table 7.1 summarizes the expected effects. The extended MNL model estimates these interactions.

Table 7.1 - Interaction effects of factors

	Alternative hydrogen design	**Willingness To Pay for reliability**
Heating habits & housing characteristics		
- *Indoor temperature day*	X	X
- *Indoor temperature night*	X	X
- *Occupancy*	X	X
- *Insulation*	X	X
- *Connection gas grid*	X	
- *Energy-saving measures*	X	X
- *Shower*		X
- *Building year*	X	X
Socio-demographic and economic variables		
- *Income*	X	X
- *Education level*	X	X
- *Household size*		X
- *Age*	X	X
- *Homeowner*	X	

- *Gender*	X	X
- *Living area*	X	X
- *Insights gas bill*		X
Attitudes		
- *The expectation of using sustainable heating*	X	X
- *Expectation of hydrogen*	X	
- *The expectation of time and money*	X	X

First, the MNL model is extended by the factors that might influence the choice of an alternative hydrogen design. All factors expected to influence this choice are added to the utility functions of the hydrogen alternatives. After the model estimation, the insignificant parameters on a 95% significance level are left out, and the model is estimated again. The significant interaction effects that influence the choice for a sustainable hydrogen alternative are:

- Whether a respondent rents or owns a house (Own);
- The expectation of using sustainable heating (SUS);
- The expectation of hydrogen (HYD).

The other estimates were not significant and left out of further research.

For analyzing the influence of the explanatory factors on the WTP, an interaction effect between the cost attribute and the explanatory factor is created and added to the utility functions. Interaction effects are made for all explanatory factors that might influence the WTP. After the first model estimations, the insignificant interaction effects are left out, and the model is estimated again. The factors that significantly (on a 95%-significance level) influence the WTP for reliability are:

- Insights in the gas use (Ins);
- Amount of insulation measures taken to insulate the house (Ins1 & Ins2);
- The expectation of using sustainable heating (SUS);
- Maintained indoor temperature during the day (TempD);
- The expectation of time and money (TM).

The significant interaction effects are added to the extended MNL model. These factors influence the choice of the respondents for an alternative hydrogen design or the WTP for reliability. Section 8.2 shows the effect of these factors.

The extended MNL model consists of all the attributes together with the significant interaction effects. The systematic utility functions for all alternatives of the final extended MNL model are:

$$\begin{aligned} V_{HydrogenA} = {} & ASC_{Hydrogen} + \beta_{Cost} * CostA + \beta_{Time} * TimeA + \beta_{Temp} * TempA + \beta_{Room1} \\ & * RoomA1 + \beta_{Room2} * RoomA2 + \beta_{CostTempD} * CostA * TempD + \beta_{CostIns1} \\ & * CostA * Ins1 + \beta_{CostIns2} * CostA * Ins2 + \beta_{CostIns} * CostA * Ins + \beta_{CostSUS} \\ & * CostA * SUS + \beta_{CostTM} * CostA * TM + \beta_{Own} * Own + \beta_{SUS} * SUS + \beta_{HYD} \\ & * HYD \end{aligned}$$

$$\begin{aligned} V_{HydrogenB} = {} & ASC_{Hydrogen} + \beta_{Cost} * CostB + \beta_{Time} * TimeB + \beta_{Temp} * TempB + \beta_{Room1} \\ & * RoomB1 + \beta_{Room2} * RoomB2 + \beta_{CostTempD} * CostB * TempD + \beta_{CostIns1} \\ & * CostB * Ins1 + \beta_{CostIns2} * CostB * Ins2 + \beta_{CostIns} * CostB * Ins + \beta_{CostSUS} \\ & * CostB * SUS + \beta_{CostTM} * CostB * TM + \beta_{Own} * Own + \beta_{SUS} * SUS + \beta_{HYD} \\ & * HYD \end{aligned}$$

$$V_{Natural\ gas} = \beta_{Cost} * CostA + \beta_{Time} * TimeC + \beta_{Temp} * TempC + \beta_{Room1} * RoomC1 + \beta_{Room2} * RoomC2 + \beta_{CostTempD} * CostC * TempD + \beta_{CostIns1} * CostC * Ins1 + \beta_{CostIns2} * CostC * Ins2 + \beta_{CostIns} * CostC * Ins + \beta_{CostSUS} * CostC * SUS + \beta_{CostTM} * CostC * TM$$

The first part of the systematic utility function displays the standard MNL model, with the alternative specific constant and the parameters for the attributes. "$ASC_{Hydrogen}$" displays the alternative specific constant for the hydrogen alternative. This constant is zero in the natural gas alternative. The parameters "$\beta_{Cost}, \beta_{Time}$ and β_{Temp}" are the parameters for the continuous attributes cost reduction, time of constraint, and the indoor temperature. The attribute amount of rooms is dummy coded (see section 5.2 and 6.1), and two parameters are estimated, "β_{Room1} and β_{Room2}".

The second part includes significant socio-demographic and economic, latent, and habit variables. The parameters "$\beta_{CostTempD}, \beta_{CostIns1}, \beta_{CostIns2}, \beta_{CostIns}, \beta_{CostSUS}$ and β_{CostTM}" show the interaction effect between the cost reduction and respectively the maintained indoor temperature, the number of insulation measures, the insights in the gas use, the latent factor expectation of time and money, and the expectation to use sustainable heating. These parameters estimate the influence on the WTP for reliability.

The last part of the systematic utility function for the hydrogen alternatives includes the parameters "β_{Own}, β_{SUS} and β_{HYD}". These parameters analyze the impact of whether the respondent is homeowner, has the expectation using sustainable heating, or has a positive expectation of hydrogen on the choice for an alternative hydrogen system.

Table 7.2 shows the values for the parameters of both MNL models, together with their standard error and significance (p-value). The standard error of a parameter measures the uncertainty that comes with the estimate. It indicates when another sample (with the same sample size) is taken, the parameter estimates would be the same. Smaller standard errors imply that it is likely that another sample will give (almost) the same parameter estimates. Usually, a high absolute value of the parameter estimate together with a low standard error results that the parameter is more likely to be significant, which can be seen in the formula: $t - value = \hat{\beta}/SE(\hat{\beta})$. A t-value > 1.96 implies that the parameter estimate is significant at a 5% interval (Chorus, 2019).

Table 7.2 - Estimates MNL models

Variables	**Base MNL**			**Extended MNL**		
	Value	Std. error	P-value	Value	Std. error	P-value
ASC_Hydrogen	0,951	0,183	0,00	-3,14	0,517	0,00
Beta_Cost	0,00460	0,000592	0,00	0,00961	0,00320	0,00
Beta_Room1	-0,530	0,0862	0,00	-0,564	0,0899	0,00
Beta_Room2	-0,00438	0,0771	0,95*	0,00595	0,0796	0,94*
Beta_Temp	0,314	0.0196	0,00	0,330	0,0204	0,00
Beta_Time	-0,00995	0,00306	0,00	-0,0110	0,00311	0,00
Beta_CostIns	-	-	-	-0,000944	0,000442	0,03
Beta_CostIns1	-	-	-	-0,00205	0,000447	0,00
Beta_CostIns2	-	-	-	-0,000845	0,000407	0,04
Beta_CostSUS	-	-	-	0,00164	0,000505	0,00
Beta_CostTempD	-	-	-	-0,00198	0,000255	0,00
Beta_CostTM	-	-	-	-0,00147	0,000406	0,00
Beta_HYD	-	-	-	0,299	0,0520	0,00
Beta_OWN	-	-	-	-0,310	0,0692	0,00
Beta_SUS	-	-	-	0,647	0,0882	0,00

*Not significant at a 95% significance level

Table 7.2 shows that the alternative specific constant for hydrogen is positive in the base MNL model, whereas the constant has a negative value in the extended MNL model. By adding a constant to the utility functions of the hydrogen alternative, the mean preference for an alternative hydrogen design can be measured. The constant captures the average utility not covered in the rest of the systematic utility. In this research, the constant displays the average inclination that households love or hate the hydrogen system with an alternative design. In the extended MNL model, extra variables are added to the systematic utility function, and the explainable power of the model goes up. The added explanatory factors explain some of the average utility for choosing an alternative hydrogen design not covered in the attributes. In the base MNL model, this utility is added to the alternative specific constant and causes that the “ASC” of the base MNL is higher than the “ASC” of the extended MNL.

When the latent attitudinal factors, the ”expectation of using sustainable heating,” and the “expectation of hydrogen” are removed from the extended MNL model, a positive value of 1,58 for the alternative specific constant is obtained. The change to a positive value implies a mean preference for a hydrogen system with a lower level of reliability. When adding the latent factors, it is hard to interpret the alternative specific constant. It can be stated that the respondents that expect to use sustainable heating and have a positive expectation of hydrogen, on average, have a preference for an alternative hydrogen design, with a lower level of reliability and a reduction in the cost.

7.3 Mixed Logit (ML) model

The Mixed Logit (ML) model is estimated based on the extended MNL model. The extended MNL model has a significantly higher model fit than the base MNL model. Moreover, the included significant explanatory factors are based on literature. Therefore, this research assumes that explanatory variables influence the choice for a hydrogen system with a lower level of reliability or the WTP for reliability. The ML model estimation includes the significant interaction effects of the extended MNL model. Section 7.1 discusses the reasons to estimate an ML model.

The ML models estimated in this research should correct for panel effects. It is expected that the choices of the same individuals are correlated. If someone chooses a hydrogen alternative with another level of reliability, he/she will likely choose an alternative hydrogen design again. The panel ML models correct for this, while the estimated extended MNL model wrongly assumes that all choices are equally important for the estimations of the parameters, which leads to biased estimates.

Three different panel ML models are estimated, an error component panel ML model, a taste panel ML model, and a combined ML model. The error component ML model (also called a preference ML model) analyzes the unobserved heterogeneity for the alternative hydrogen design by adding an additional error term to the utility function. This error term will investigate whether there is heterogeneity for the average preference for an alternative hydrogen design. Moreover, it will ensure the utility of the alternative hydrogen designs will go up and down together. The error term accounts for the nesting effects between the two hydrogen systems with a different level of reliability. After all, these alternatives share common factors.

The taste ML model analyzes the observed heterogeneity in the choice model parameters and allows the parameter estimates to vary randomly across the sample. This addition will test whether there is heterogeneity in the sample for the utility of the attributes. Finally, the combined ML model tests the unobserved and observed heterogeneity together in the sample. Appendix J addresses the model fit of all three models. The parameter estimations can be found in Appendix K, Table K.1, and Table K.2. The estimations are based on 200 Halton draws.

In the taste ML model, the parameters can vary randomly across the sample. The parameters vary according to a defined distribution. This research expects that every respondent is likely to prefer more cost reduction over less cost reduction. Therefore, the cost reduction attribute follows a log-normal distribution. The cost reduction attribute contains zeros in the data set for natural gas alternatives. A log-normal distribution cannot be estimated with zeros in the data set, since it will cause a very high initial log-likelihood. Replacing all zeros of the cost attribute by “one” allows running the model with a log-normal distribution of the cost attribute. However, it became apparent that the model fit of this model was worse than the model fit of the model with the normally distributed parameter for the cost reduction attribute with values of zero. Furthermore, almost all attributes become insignificant. Consequently, this report uses a normal distribution for the cost reduction attribute.

For the time constraint attribute, there is the expectation that there is a dislike for a more extended period with a time constraint. Therefore, the time constraint attribute is estimated based on a negative log-normal distribution. However, similar to the cost reduction attribute, the data set contains zeros for all natural gas alternatives. All zeros of the data set are replaced by “one” for the time constraint attribute. However, the model fit of the estimated model is worse for the model with the negative log-normal distribution than the model with the normal distribution of the time constraint parameter. Consequently, a normal distribution is used for the time constraint attribute.

For the attributes maximum indoor temperature and the number of rooms, the log-normal distribution is not more likely to display the distribution of the parameters than the normal distribution. It is not per definition that a higher temperature is more likely to be preferred based on the wide range than can be given for the preferred indoor temperature. Also, for the number of rooms, this cannot be stated. There is a real possibility that the house contains only three rooms. Consequently, the option of all rooms is not more likely to be preferred than three rooms. Therefore, all the attributes are distributed normally. Also, other distributions can be considered, such as the triangular distribution or the truncate of the normal distribution. However, due to time constraints, only the normal and the log-normal distribution are considered.

The results displayed in Appendix K show that the estimated sigmas for the taste and the preference heterogeneity are significant and do not equal zero. There is observed and unobserved heterogeneity in the population. Ignoring one of these heterogeneities might lead to biased parameter estimates. Moreover, the combined ML model has the best model fit based on the likelihood ratio test and the Rho-Squared test. Concludingly, the combined ML model should be used instead of the error component panel ML model or the taste panel ML model.

The systematic utility functions for the combined ML model are:

$$\begin{aligned} V_{HydrogenA} = {} & ASC_{Hydrogen} + \upsilon_{n,Hydrogen} + \beta_{n,CostA} * CostA + \beta_{n,TimeA} * TimeA + \beta_{n,TempA} \\ & * TempA + \beta_{n,Room1} * RoomA1 + \beta_{n,Room2} * RoomA2 + \beta_{CostTempD} * CostA \\ & * TempD + \beta_{CostIns1} * CostA * Ins1 + \beta_{CostIns2} * CostA * Ins2 + \beta_{CostIns} \\ & * CostA * Ins + \beta_{CostSUS} * CostA * SUS + \beta_{CostTM} * CostA * TM + \beta_{Own} * Own \\ & + \beta_{SUS} * SUS + \beta_{HYD} * HYD \end{aligned}$$

$$\begin{aligned} V_{HydrogenB} = {} & ASC_{Hydrogen} + \upsilon_{n,Hydrogen} + \beta_{n,CostB} * CostB + \beta_{n,TimeB} * TimeB + \beta_{n,TempB} \\ & * TempB + \beta_{n,Room1} * RoomB1 + \beta_{n,Room2} * RoomB2 + \beta_{CostTempD} * CostB \\ & * TempD + \beta_{CostIns1} * CostB * Ins1 + \beta_{CostIns2} * CostB * Ins2 + \beta_{CostIns} \\ & * CostB * Ins + \beta_{CostSUS} * CostB * SUS + \beta_{CostTM} * CostB * TM + \beta_{Own} * Own \\ & + \beta_{SUS} * SUS + \beta_{HYD} * HYD \end{aligned}$$

$$\begin{aligned} V_{Naturalgas} = {} & \beta_{CostC} * CostC + \beta_{TimeC} * TimeC + \beta_{TempC} * TempC + \beta_{Room1} * RoomC1 \\ & + \beta_{Room2} * RoomC2 + \beta_{CostTempD} * CostC * TempD + \beta_{CostIns1} * CostC * Ins1 \\ & + \beta_{CostIns2} * CostC * Ins2 + \beta_{CostIns} * CostC * Ins + \beta_{CostSUS} * CostC * SUS \\ & + \beta_{CostTM} * CostC * TM \end{aligned}$$

$\upsilon_{n,Hydrogen} \sim N(0, \sigma_{\upsilon_{Hydrogen}})$
$\beta_{n,Cost} \sim N(\beta_{Cost}, \sigma_{\beta_{Cost}})$
$\beta_{n,Time} \sim N(\beta_{Time}, \sigma_{\beta_{Time}})$
$\beta_{n,Temp} \sim N(\beta_{Temp}, \sigma_{\beta_{Temp}})$
$\beta_{n,Room1} \sim N(\beta_{Room1}, \sigma_{\beta_{Room1}})$
$\beta_{n,Room2} \sim N(\beta_{Room2}, \sigma_{\beta_{Room2}})$

7.3 Comparison MNL and ML models

Section 7.1 gives the hypothesis that this research should a panel Mixed Logit model that corrects for the observed and unobserved heterogeneity. A comparison must be made between the results of both models to determine which model is best suited to answer the research question of this research. By analyzing the outcomes of both models, a deliberate decision can be made about which model is best suitable in this research. This section analyzes and compares the results of both models.

First, the estimates and the significance of the sigmas calculated in the combined ML are analyzed. If the estimated sigmas in the ML model are statistically significant, and the sigmas do not equal zero, observed and unobserved heterogeneity is present in the sample. Table 7.3 shows that the estimates of the sigmas for capturing the taste and the preference heterogeneity do not equal zero and that the sigmas are significant (except for the time constraint). This result implies that the combined ML model should be considered instead of the MNL model (Chorus, 2018). If heterogeneity is essential but neglected, it can result in the overestimation of the WTP for reliability (Espino, et al., 2008). However, it is unknown what the exact influence is when the wrong assumption is made related to the heterogeneity (Van den

Berg, 2011). There is heterogeneity in the sample. This heterogeneity should not be neglected, to minimize the possibility of overestimating the WTP for reliability. This raises the though to use the panel ML model over the MNL model.

Secondly, the model fit of the two models is compared based on the likelihood ratio test and the Rho Squared. Based on both comparisons, the combined ML model fits the data better (Appendix J). This comparison also implies that the combined ML model should also be used to analyze the data.

Thirdly, when comparing the estimations of the MNL and the combined ML model (see Table 7.2 and Table 7.3), it becomes apparent that some coefficients are significant in the MNL model, while they are not significant in the ML models. These are biased estimates in the MNL model. An explanation for these biased estimates is that the MNL model assumes that the choices made by the same individual are not correlated. The MNL model assumes that every choice observation contains the same amount of information when estimating the value of the parameters. The standard error of the parameter is underestimated, and the t-values are overestimated. Assigning too much certainty to the parameter estimate causes that parameters become significant, while they are not (Chorus, 2018). The same effect occurs when a model wrongly ignores taste and preference heterogeneity.

Using an ML model makes it more difficult to obtain insights into the WTP for reliability. However, based on the literature and the estimated sigmas, it is expected that there is taste and preference heterogeneity. Moreover, due to the significantly better model fit of the ML models over the MNL models, it is expected that the choices of individuals are correlated. Combining gives that in this research, there is chosen to use the combined ML model for analyzing the data, to overcome the possibility that the parameters are biased and overestimate the value of the WTP.

From analyzing the outcomes of the MNL models and the combined ML model shows that the absolute value of the parameters is higher in the ML model than in the MNL model. The higher absolute value is caused by the addition of the sigmas in the ML model. The sigmas explain a part of the error-term "ε" since less randomness is left in the total utility function. The variance of the ε is normalized and cannot decrease. The model corrects for this by increasing the parameter estimates (Chorus, 2018).

7.4 Combined ML model

The number of Halton draws for the combined ML model is increased to create stable results. The number of draws is increased until the estimations hardly changed, and the result becomes stable. In total, 800 draws are used for the final estimation of the combined ML model. A further increase to 1600 Halton draws did not give significantly different results. From the taste ML model, it already became apparent that the heterogeneity (the sigma) calculated for the time parameter was insignificant. This insignificance was also found when increasing the number of Halton draws in the combined ML model. Therefore, the time parameter is not varied randomly in the final combined ML model. Table 7.3 shows the final parameter estimations of the combined ML model.

The expectation is that including latent factors in the choice model has added value for Stedin (as is discussed in section 7.1). However, this research chooses to estimate a combined ML model without the latent factors next to the complete combined ML model. This decision is based on two reasons. First, due to the criticism of hybrid choice models. Second, due to the significant effect of the attitudinal factors on the alternative specific constant, and the difficulty to interpret the mean preference for an alternative hydrogen system due to the incorporation of the attitudinal factors.

Table 7.3 shows the parameter estimations of both models. Besides the estimate for the alternative specific constant for the hydrogen alternatives and the sigma for hydrogen, the parameter estimates do not differ significantly in both models. They keep within two times the standard error. The significant differences between both models are circled in red in Table 7.3.

Table 7.3 - Parameters estimates Final ML Combined

Variables	**Final ML Combined** *(800 runs)*			**Final ML Combined** *(800 runs, without latent factors)*		
	Value	Std. error	P-value	Value	Std. error	P-value
ASC_Hydrogen	-6,27	1,27	0,00	4,13	0,445	0,00
Beta_Cost	0,0127	0,00643	0,05	0,0206	0,00274	0,00
Sigma_Cost	0,0109	0,00135	0,00	0,00875	0,00136	0,00
Beta_Room1	-0,706	0,142	0,00	-0,771	0,128	0,00
Sigma_Room1	0,906	0,203	0,00	0,722	0,189	0,00
Beta_Room2	0,114	0,138	0,41*	0,178	0,123	0,15*
Sigma_Room2	-1,00	0,181	0,00	-1,02	0,152	0,00
Beta_Temp	0,490	0,0410	0,00	0,418	0,0322	0,00
Sigma_Temp	0,340	0,0457	0,00	0,250	0,0432	0,00
Beta_Time	-0,0176	0,00468	0,00	-0,0134	0,00414	0,00
Sigma_Hydrogen	3,95	0,377	0,00	6,86	0,650	0,00
Beta_CostIns	-0,00346	0,00113	0,00	-0,00290	0,000985	0,00
Beta_CostIns1	-0,00102	0,00110	0,35*	1,21e-005	0,00101	0,99*
Beta_CostIns2	-0,00274	0,00107	0,01	-0,00278	0,000944	0,00
Beta_CostSUS	0,00248	0,000877	0,01	-	-	-
Beta_CostTempD	-0,00344	0,000683	0,00	-0,00322	0,000593	0,00
Beta_CostTM	-0,00132	0,000995	0,18*	-	-	-
Beta_HYD	0,736	0,173	0,00	-	-	-
Beta_OWN	0,0118	0,211	0,96*	0,0652	0,207	0,75*
Beta_SUS	1,20	0,197	0,00	-	-	-
**Not significant at a 95% significance level*						
Rho-Square	0,468			0,446		
Final log likelihood	-1692,282			-1761,548		
LRS	2979,621			2837,680		

8. Results from a hybrid and discrete choice model

This chapter presents and interprets the results of the discrete choice model. The first section elaborates on the preferences of the households related to the different design variables. After that, section 8.2 analyzes the influence of different explanatory variables on the preference of the households. Section 8.3 determines and discusses the Willingness To Pay (WTP) for reliability. Finally, section 8.4 summarizes the main findings.

8.1 Preference of the public for the different design variables

This research analyzes the preference of the households related to the design of a sustainable hydrogen system used for heating. The design of the hydrogen system differs in the amount of cost reduction, compared to the current system, and the amount of time at which a different number of rooms can be heated at a specified maximum temperature. The cost reduction displays the cost for a heating system, whereas the time, number of rooms and the maximum temperature display the reliability of the system. This report uses the cost reduction to determine the WTP for the different reliability attributes. The WTP of the reliability attributes creates insights into the WTP for the reliability of a hydrogen system.

Each choice set showed to the respondents consisted of three alternatives, two sustainable hydrogen systems with different levels for the costs and reliability, and one natural gas system that depicts the current system used for heating. In this way, the respondents are not forced to choose one of the alternative hydrogen designs, but can also opt for the current system.

For every attribute, the Mixed Logit model calculates a parameter estimate, see Table 7.3. The design variable for the number of rooms that can be heated is dummy coded, and two parameters are estimated for this attribute. The estimated parameters for the number of rooms heated represent the utility difference with the reference value of all the rooms. The utility contribution of the different levels of the other attributes is estimated by multiplying the levels of the attribute with the parameter estimate. Further, to compare the importance of the different attributes, the relative importance of the attributes must be calculated. The relevance importance takes into account the chosen range of the attribute levels.

8.1.1 The mean preference of an alternative hydrogen design

Within the first model, attitudinal variables are added to the systematic utility functions, making it harder to interpret the alternative specific constant. The alternative specific constant of the model that does not include the latent factors show a positive and significant value for the hydrogen constant. A positive alternative constant indicates that there is a mean preference for the introduction of an alternative design for a hydrogen system, see Table 8.1.

The sigma of the alternative hydrogen design from the model without the attitudinal factors (6,95) implies much heterogeneity in the unobserved preference for introducing a hydrogen system with a lower level of reliability, see Table 8.1. Less explanatory variables are estimated in this model compared to the model, including latent variables. Therefore, the utility of an alternative hydrogen design is, to a lower extent, explainable by the observed variables. On average, there is a mean preference for the use of an alternative hydrogen system, but also negative values occur.

Table 8.1 - Estimates alternative specific constant, without latent factors

	Estimate	**Standard error**
ASC_Hydrogen	4,13	0,445
Sigma_Hydrogen	6,86	0,650

The sigma of the alternative hydrogen design from the model with the attitudinal factors (3,95) implies that there is much heterogeneity in the unobserved preference for introducing an alternative design for hydrogen, see Table 8.2. The utility of an alternative hydrogen design that cannot be explained by the observed variables has a broad range. In this range, predominantly negative values occur, but also positive values.

Table 8.2 - Estimates alternative specific constant, with latent factors

	Estimate	**Standard error**
ASC_Hydrogen	-6,27	1,27
Sigma_Hydrogen	3,95	0,377

When incorporating the attitudinal values, there is a mean preference for maintaining the current natural gas design. The attitude towards the “expectation of using sustainable heating” and the “expectation of hydrogen” significantly influences the alternative specific constant. This influence implies that households with a higher expectation of using sustainable heating and have a positive expectation of hydrogen in the built environment, on average, accept a hydrogen system with a lower level of reliability. The influence can be caused by the fact that the respondents with a strong preference for sustainable heating and expect that hydrogen is an excellent sustainable resource are part of a so-called “frontrunner” group in terms of sustainability. They are frontrunners in the transition towards sustainability and want to induce change. This group probably sees the reduced level of reliability and a slightly less level of comfort just as a precondition for the implementation of the hydrogen infrastructure. This supports the hypothesis given in section 7.1.

8.1.2 Influence of cost reduction on the preference of a heating alternative

The parameter for cost reduction is positively valued, as is expected. If the other variables remain constant, a higher cost reduction results in a higher utility of the alternative. Table 8.3 displays the estimates of the cost reduction attribute, while Figure 8.1 visualizes the utility contribution of the cost reduction attribute.

Table 8.3 - Estimates of cost reduction attribute

	Estimate	**Utility contribution**	**SE**	**Range**	**Utility range contribution**	**Relative importance**
Beta_Cost	0,0127		0,00643	210	2,667	38%
- *€0/year* - *€80/year* - *€145/year* - *€210/year*		- 0 - 1,016 - 1,8415 - 2,667				
Sigma_Cost	0,0109		0,00135			

There is some heterogeneity in taste for the utility obtained from the amount of cost reduction. The attribute has primarily positive values, but also some negative values occur. The primarily positive values imply that, on average, there is a mean increase in utility for the alternative hydrogen system when the cost reduction increases (while the rest remains constant). At the same time, there are also some respondents whose utility of the alternative hydrogen system decreases when the cost reduction increases. Different reasons exist to explain these negative values. First, the respondent can choose the natural gas alternative, with no cost reduction. Second, some respondents might choose another alternative, with a lower cost reduction since they consider another attribute level too low. For example, if a respondent considers 17°C as a too low indoor temperature, it will not matter how much cost reduction is given to him/her. He will not prefer this alternative. The sensitivity of every respondent for the trade-off between cost reduction and reliability differs. Another explanation can be that the cost attribute is distributed according to a normal distribution. In this distribution, negative values can occur. On average, the respondents have a slight preference for a cost reduction in return for a lower level of reliability of the hydrogen system.

When comparing the utility contribution of the attributes with each other, one can see that the cost reduction significantly influences the choice for which heating alternative is preferred. After the maximum indoor temperature, the cost reduction mostly influences the choice for a heating alternative.

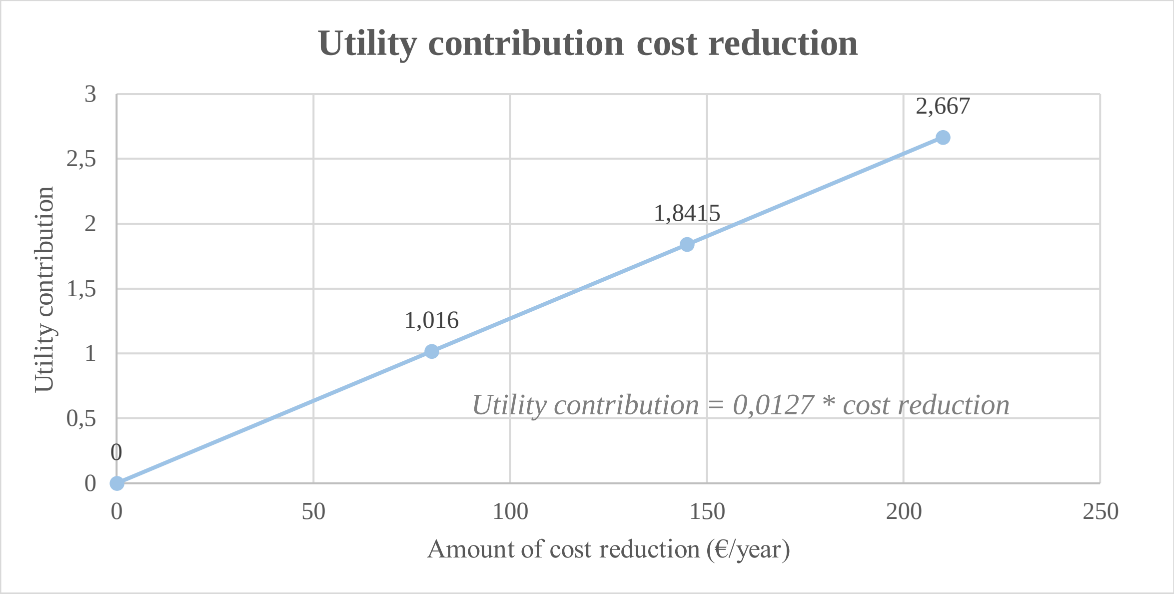

Figure 8.1 - Utility contribution of cost reduction

8.1.3 Influence of time with demand constraints on the preference of a heating alternative

As expected, the time constraint attribute is valued negatively. An extended period of constraints is, in general, not valued positively. When analyzing the utility contribution of the time constraint, one can see that the respondents negatively value a more extended period at which the demand constraint holds, in case the other variables remain constant, see Figure 8.2 and Table 8.4.

Table 8.4 - Estimates of time constraint attribute

	Estimate	Utility contribution	SE	Range	Utility range contribution	Relative importance
Beta_Time	-0,0176		0,00468	29	0,5104	7%
- *0 hours/year* - *3 hours/year* - *10 hours/year* - *29 hours/year*		- 0 - -0,0528 - -0,176 - -0,5104				

When increasing the number of Halton draws, it became apparent that the sigma for the time attribute is not significant. The insignificant sigma implies that there is not much heterogeneity in the sample in the utility obtained from a time constraint. There is consensus about the dislike for the amount of time with a constraint.

When comparing the relative importance of the time constraint to the other attributes, one can conclude that this attribute plays the smallest role for the choice for or against an alternative hydrogen design than the other attributes, see Table 8.4.

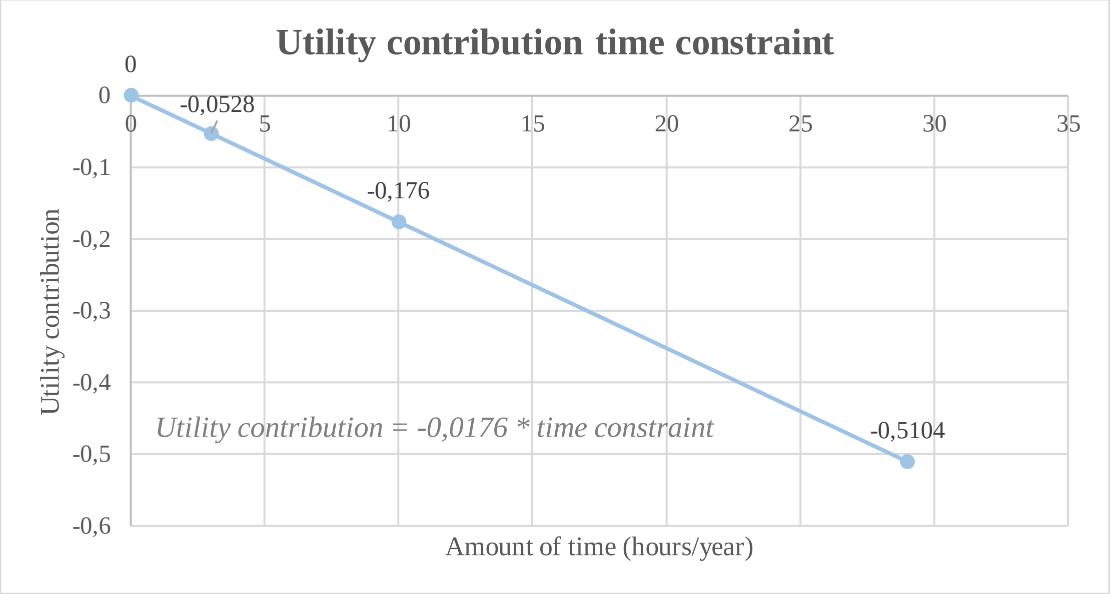

Figure 8.2 - Utility contribution of time constraint

8.1.4 Influence of the indoor temperature on the preference of a heating alternative

On average, households value a higher maximum temperature more positively than a lower maximum indoor temperature. Households prefer a maximum indoor temperature of 19℃ over a maximum temperature of 17℃. The positive course is expected since households generally dislike a more restricted constraint (lower maximum indoor temperature). Figure 8.3 visualizes the utility contribution. Table 8.5 shows the estimations of the maximum indoor temperature attribute.

Table 8.5 - Estimates of maximum indoor temperature attribute

	Estimate	Utility contribution	SE	Range	Utility range contribution	Relative importance
Beta_Temp	0,490		0,0410	6	2,94	42%
- *17℃* - *19℃* - *23℃*		- 8,33 - 9,31 - 11,27				
Sigma_Temp	0,340		0,0457			

From the literature, it became apparent that there is heterogeneity in the preferred indoor temperature. Within this research, also significant taste heterogeneity was found for the maximum indoor temperature. Due to the heterogeneity, the beta for maximum temperature can take positive as well as negative values. However, predominantly positive values occur for the maximum indoor temperature. On average, the utility of an alternative increases when the maximum indoor temperature increases. However, the utility of the alternative decreases for several respondents when the maximum indoor temperature increases. A cause for the decrease in utility can be that an indoor temperature of 19℃ is considered sufficient and that a further increase in the indoor temperature does not lead to a higher utility. The obtained negative values can also be the consequence of the normally distributed indoor temperature parameter. The normal distribution is symmetrical, and a counter-intuitive sign can be given to the attribute.

The relative importance of the maximum indoor temperature is high. See Table 8.5. When comparing the utility contribution of the maximum indoor temperature to the other attributes, one can state that the maximum indoor temperature influences the choice for an alternative the most.

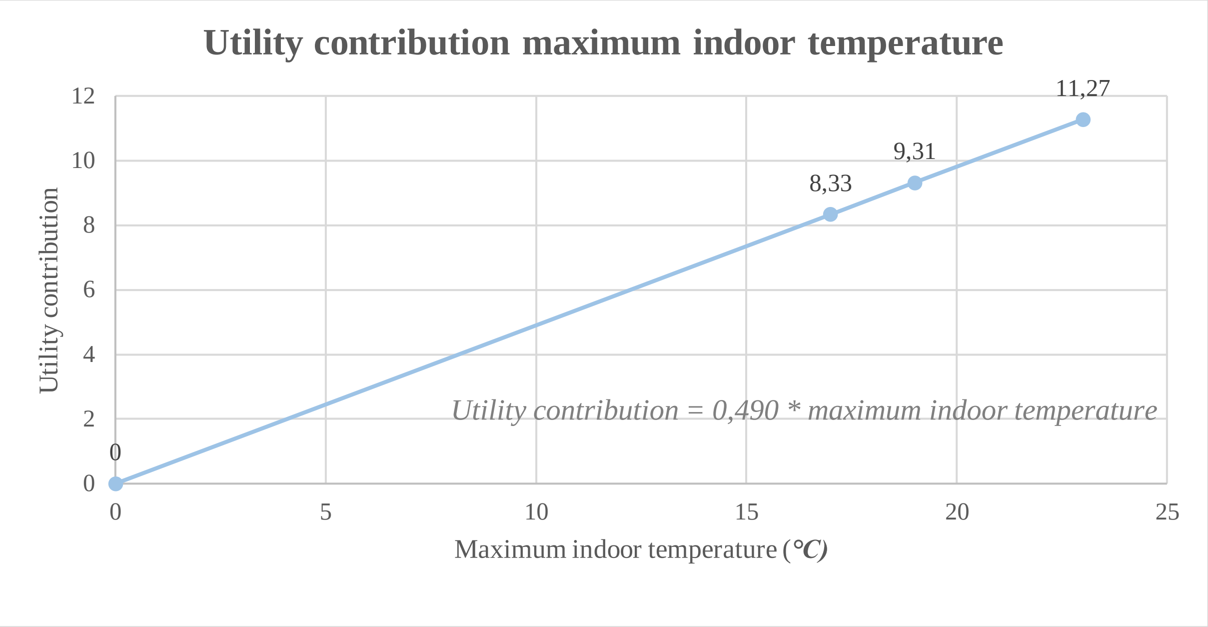

Figure 8.3 - Utility contribution of maximum indoor temperature

8.1.5 Influence of the number of rooms heated on the preference of a heating alternative

The number of rooms heated is dummy coded. The parameter estimates display the utility obtained from “one-room heated” and “three rooms heated,” compared to the reference value of “all rooms heated.” Table 8.6 shows that a maximum of three rooms heated (Beta_Room2) during demand constraints is valued the most by the respondents. This attribute level has a positive utility, and the alternative with “three rooms” heated is most likely chosen (ceteris paribus). The respondents dislike the restriction that one room can be heated. This attribute level has a negative utility. Based on the negative utility, only one-room heated is assumed to be insufficient. For all the utilities, see Table 8.6 and Figure 8.4.

Table 8.6 - Estimates of the maximum amount of rooms heated attribute

	Estimate	Utility contribution	SE	Range	Utility range contribution	Relative importance
Beta_Room1 **Beta_Room2**	-0,706 0,114*		0,142 0,138		0,82	12%
- *1 room* - *3 rooms* - *All rooms*		- -0,706 - 0,114 - 0		1 1 1		
Sigma_Room1 **Sigma_Room2**	0,906 1,00		0,203 0,181			

There is significant heterogeneity in taste for the maximum amount of rooms heated. The parameter estimates can take both positive and negative values. On average, the utility of a heating alternative decreases when only one room is heated. However, there are also respondents whose utility increases when only one room is allowed to be heated. Plausible explanations for the increase in utility for several respondents can be that households do not experience the maximum of one-room heated as a problem because they think the cost reduction is sufficient, the temperature of the room is high enough or the period of constraints is not very long. Alternatively, they think that only one-room heated does not severely reduce their level of comfort. They, for example, have a one-room or two-rooms apartment. Also, an explanation can be that some households have a strong preference for a sustainable system used for heating, even though only one-room is allowed to be heated. Finally, the positive values can occur due to the normal distribution.

For a maximum of three rooms, the mean utility is positive. So, on average, the utility increases for the alternative design if three rooms are allowed to be heated. However, based on the heterogeneity, some respondents' utility for an alternative decreases when only three rooms can be heated. The expectation is that these respondents prefer to heat more rooms than only three. Possible reasons can be that those respondents live in bigger houses. The respondents living in a bigger house will experience more comfort loss with the constraint were only three rooms are allowed to be heated than respondents living in a smaller house with fewer rooms. Another reason could be that respondents do not want to reduce the level of reliability by constraining the number of rooms that can be heated. Further, the respondents can also choose several times the natural gas alternative. Lastly, it can be a consequence of the normal distribution of the parameter. The parameter estimate for "three rooms heated" (Beta_Room2) is not significant on a 5%-level. The insignificance means that the exact value in the population is not known. Therefore, only conclusions for this attribute can be drawn for the sample.

When comparing the importance of this attribute with the other attributes, it can be stated that this attribute plays a smaller role than the amount of cost reduction and the maximum indoor temperature. Nevertheless, the amount of rooms heated plays a slightly more prominent role in choosing an alternative design than the period with constraints.

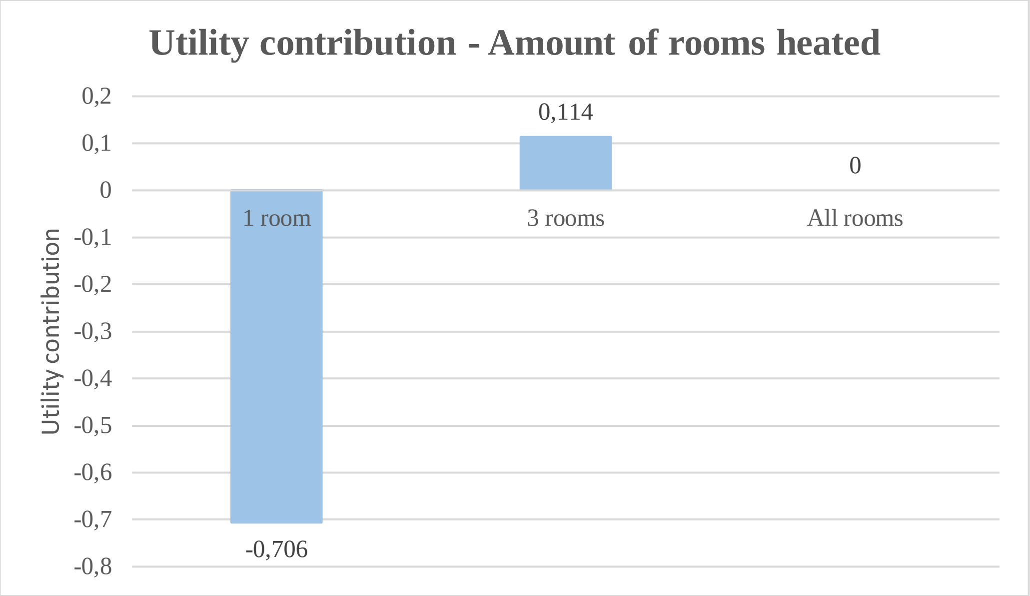

Figure 8.4 - Utility contribution of the maximum amount of rooms heated

8.1.6 Conclusions about the influence of the design variables

All the estimated parameters are of the expected sign. The cost reduction and indoor temperature are predominantly valued positively. A higher utility is obtained if these variables increase (while the other variables remain the same). For both attributes, heterogeneity exists about the obtained utility. The time constraint attribute is valued negatively, as was expected. There is a general dislike for a more extended period with constraints, and no significant heterogeneity exists in the time constraint attribute. Households agree about the dislike for a more extended period with demand reductions.

There is a general dislike for situations where only one room is allowed to be heated. However, there is heterogeneity in the utility obtained from this level. Furthermore, there is a general preference for heating only three rooms compared to all rooms. A plausible explanation would be that respondents prefer a hydrogen system and accept a lower level of reliability. The natural gas alternative did not have any constraints on the number of rooms allowed to be heated. However, the estimation for "three rooms heated" is not significant, and only conclusions for the sample can be given.

The maximum indoor temperature mostly influences the choice of a heating alternative. Also, cost reduction significantly influences the choice of households. After these two attributes, the number of rooms heated mostly influenced the choice for a heating alternative. The period with constraints least influenced the choice of the respondent.

Finally, the alternative specific constant for hydrogen implies a general like for a sustainable hydrogen system with a lower level of reliability. The general like is the outcome of the model without the latent factors. On average, households prefer a hydrogen system with a lower level of reliability and cost reduction. For the general like, significant heterogeneity exists.

8.2 Influence of explanatory variables on the preference of a heating alternative

This section determines the influence of the different explanatory variables on the preference of the hydrogen system with a lower level of reliability. The influence is determined based on the outcomes of the Mixed Logit model. First, section 8.2.1 elaborates on the influence of the socio-demographic and economic variables. Sub-section 8.2.2 discusses the influence of heating habits and the housing characteristics on the preference for an alternative hydrogen design. Finally, sub-section 8.2.3 shows the influence of the attitudes of the households on the preference for an alternative hydrogen design. At the end of each subsection, intermediate conclusions about the influence of the variables are provided.

8.2.1 Influence of socio-demographic and economic variables on preference for an alternative hydrogen design

Almost none of the socio-demographic and economic variables turned out to significantly affect the willingness to use a sustainable hydrogen system or significantly influenced the WTP for reliability.

Only one socio-demographic and economic factor, namely the insights in the gas use, significantly influenced the utility obtained from a cost reduction. The value for this variable is negative, -0,00364. The variable insights in the cost are coded +1 for “yes” and -1 for “no.” The respondents that have insight into their energy costs value more cost reduction more negatively, while respondents that do not have insight into their energy costs value a higher cost reduction more positively. Respondents that have insight into their energy costs are more willing to pay for reliability, while the respondents that do not have insight into their energy costs are less willing to pay for reliability. A reason for the effect can be that respondents with insight into their energy costs are more aware of their energy use and are less sensitive to any cost reductions caused by a lower level of reliability.

Conclusion

Households that have insight into their gas use have a higher WTP for reliability. An explanation could be that this group is more aware of their gas use and know how to reduce their costs without reducing the level of comfort. Appendix L and section 8.3 show the exact effect on the WTP for reliability.

8.2.2 Influence of heating habits and housing characteristics on preference for an alternative hydrogen design

Also, almost none of the heating habits and housing characteristics turned out to be significant in the ML model. The significant variables are the insulation of the house, the maintained indoor temperature, and whether a respondent owns or rents a house. The first two mentioned attributes have an interaction effect with the cost reduction, while whether the respondent owns a house directly influences the choice of a heating system.

Insulation of the house

The attribute for insulation is effect coded, and the estimates for the insulation (Ins1 and Ins2) give the difference in utility compared to the average utility of zero. The first variable estimated (Beta_CostIns1) displays the interaction effect of the cost reduction, and the respondents living in poorly insulated houses. The second variable (Beta_CostIns2) is the interaction effect between respondents living in houses with some insulation measures taken and the cost reduction. Both interactions are negative. Thus, respondents living in a house with inadequate insulation or with only some insulation measures taken dislike a cost reduction as compensation for reducing the level of reliability. This group has a higher WTP for reliability.

Both interaction variables of the cost and insulation (Beta_CostIns1 and Beta_CostIns2) should be multiplied by -1 to determine the interaction between the cost reduction and households living in well-insulated houses. The multiplication is needed due to the effect coding (see section 6.1). The determined interaction effect is positive and implies that respondents living in well-insulated houses are more sensitive for cost reductions and are less willing to pay for reliability. They prefer a higher cost reduction.

The first variable for insulation is not significant, based on the outcomes of the ML model. The relation between households living in poorly insulated houses and the cost reduction cannot be formulated on the population level. Nevertheless, one can state that households living in well-insulated houses have a lower WTP for reliability than households living in houses with only a few insulation measures taken.

Maintained indoor temperature
The estimated interaction effect between the indoor temperature and the cost reduction is negative. The negative interaction implies that respondents maintaining a higher indoor temperature have a higher WTP for reliability. This report sees this influence as a logical interaction since households that maintain a higher indoor temperature have to decrease their indoor temperature more if the temperature is constrained.

For example, a constrained maximum indoor temperature of 19℃ will affect households maintaining an indoor temperature of 23℃ more than households maintaining an indoor temperature of 20℃. Households that maintain an indoor temperature of 23℃ obtain more benefit from a heating system that always delivers enough gas to heat the house until high temperatures (23℃). Households maintaining a higher indoor temperature have a higher WTP for reliability.

Own a house
Lastly, the effect of whether the respondent owns a house on the choice for a heating alternative is estimated. The effect is positive, and the variable is effect coded. The respondents that own a house prefer a hydrogen system with a lower level of reliability compared to respondents living in a rented house. This relation was not expected based on literature. A reason for this relationship could be that homeowners are more concerned about the future energy connection of their house or the cost of a new energy system and would prefer a slightly cheaper option with a lower level of reliability.

This variable is not significant in the combined ML model. Therefore, this effect cannot be translated to the population level, but only to the sample level. Therefore, this research does not further consider this effect.

Conclusion
The WTP for reliability is influenced by the quality of the insulation of the households' house. Households living in a house with several insulation measures have a higher WTP for reliability than households living in well-insulated houses. Also, the maintained indoor temperature influences the WTP for reliability. Households that averagely maintain a higher indoor temperature have a higher WTP for reliability than households maintaining a lower indoor temperature. The exact effect of both variables is estimated and discussed in Appendix L and sub-section 8.3.2.

8.2.3 Influence of attitudes on preference for a heating alternative

This section discusses the influence of the attitudes on the preference for a heating alternative based on the Mixed Logit model. All the significant variables from the extended MNL model are discussed below.

The acceptability of using sustainable heating
Two interaction effects are estimated for the attitudinal variable "expectation of using sustainable heating." The first discussed is the interaction with cost reduction. This interaction effect is positive and implies that the respondents expecting to use sustainable heating obtain more benefit from the cost reduction as compensation for the reduced level of reliability. Concludingly, these respondents are less willing to pay for reliability.

Furthermore, the Mixed Logit model estimated the influence of the respondents' expectation of using sustainable heating to choose a heating alternative. This effect is estimated to be 1,20 and has a significant effect on the choice of respondents. Subsequently, the respondents that are more willing to use sustainable heating obtain a higher utility from the hydrogen designs with a lower level of reliability. This group is more willing to choose a design with a lower level of reliability in exchange for a cost reduction.

Households that expect to use sustainable heating have a lower WTP for reliability. Moreover, these households are willing to choose a design with a lower level of reliability in exchange for money. A possible reason for this outcome is that households that expect to use a sustainable heating source see a reduction in reliability as a condition to switch to a form of sustainable heating in the built environment.

The expectation of hydrogen

The effect of the expectation of hydrogen positively influences the choice of an alternative hydrogen design. The households that expect that hydrogen is a suitable heating alternative in the built environment obtain more utility from a hydrogen system with a lower level of reliability. They are willing to choose a design with a lower level of reliability against a cost reduction.

The expectation of time and money

Lastly, the interaction effect of the "expectation of time and money" on the cost reduction is estimated. This effect is estimated negatively. This effect implies that respondents that have a negative expectation of time and money (these respondents stated that the renovation time should be short and that they expect that hydrogen is expensive) obtain a negative value from a cost reduction as compensation for a reduced level of reliability. This group has a higher WTP for reliability. The respondents with this attitude are more likely to prefer the current natural gas system, with no cost reduction.

This interaction effect turned out to be insignificant in the combined ML model, which causes that no conclusions on the population level can be stated. This interaction is not further analyzed in this research.

Conclusion

The attitudinal variables are measured on the same scale, which causes that the utility contributions can be compared to each other. The expectation of using sustainable heating influences the choice of an alternative the most. Also, the expectation of hydrogen appeared to have a significant influence on the choice of a heating alternative. Households that expect using sustainable heating and have a positive expectation of hydrogen in the built environment are likely to choose a hydrogen system with a lower level of reliability. It seems plausible to assume that this group sees the reduced level of reliability as something inevitable for the transition to a form of sustainable heating.

The expectation of using sustainable heating also influences the WTP for reliability. Households that expect to use sustainable heating have a lower WTP for reliability. Appendix L and section 8.3.2 estimate and discuss the exact effect.

8.3 Willingness To Pay for reliability

This research uses the inverse of the cost reduction attribute to estimate the Willingness To Pay (WTP) for the different attributes. The opposite of cost is cost reduction. The formula for the estimation of the Willingness To Pay is $WTP = \frac{\beta_{Reliability}}{\beta_{Price}}$ and this research uses the formula: $WTP = -\frac{\beta_{Reliability}}{\beta_{Cost\ reduction}}$.

This research bases the results on the combined ML model, in which the betas can vary randomly across the individuals. The estimation of the WTP is more complicated when using a combined ML model than an MNL model. A possible way would be to divide the mean parameter estimations of the reliability attributes by the mean parameter estimation of the cost reduction attribute. However, this estimation neglects the heterogeneity in the population and does not make use of the extra estimation effort (Sillano & Ortúzar, 2003). The outcome of this estimation will not be the mean WTP, but “a WTP value derived from the coefficients of the ‘average individual’ for each parameter” (Sillano & Ortúzar, 2003).

This report searches for the average WTP. Moreover, section 7.1 showed that there is significant heterogeneity in the population. Another way to determine the WTP in Mixed Logit models is by fixing the cost reduction attribute. Fixing the cost reduction will overcome the estimation of the WTP based on two randomly distributed parameters. The WTP distribution will follow the distribution of the reliability attribute, the nominator (Sillano & Ortúzar, 2003; Hole & Kolstad, 2012; Hasselbach & Roosen, 2015). The following formula gives the resulting WTP distribution:

$$\left.\begin{array}{c} \beta_{Reliability} \sim N\left(\mu_{Reliability}, \sigma_{Reliability}\right) \\ \beta_{Cost} \sim Fixed \end{array}\right\} \frac{\beta_{Reliability}}{\beta_{Cost}} \sim N\left(\frac{\mu_{Reliability}}{\beta_{Cost}}, \frac{\sigma_{Reliability}}{\beta_{Cost}}\right)$$

8.3.1 Willingness To Pay for the reliability attributes

To estimate the WTP, a new combined ML model is estimated. This model fixes the parameter for the cost. The model uses 800 Halton draws to create stable results. Appendix K (table K.3) shows the estimated parameters. Table 8.7 shows the WTP estimates for the reliability attributes. The WTP estimates are rounded.

Table 8.7 - WTP estimates fixed costs

Reliability attributes	**Mean**	**Sigma**
Reduce time with constraints with 1 hour	€0,60 per year	-
Increase indoor temperature with 1°C	€31 per year	€19
All rooms heated instead of 1 room	€30 per year	€42
Three rooms heated instead of all rooms	€10 per year*	€19*
Three rooms heated instead of 1 room	€40 per year*	Unknown*
** Insignificant on a 95% interval level*		

There is much heterogeneity in the average WTP for the different attributes when considering the values of the sigmas. The Mixed Logit model displays the mean of the WTP estimates. Due to the significant heterogeneity, this report estimates the 95%-confidence interval of these estimates. The following formula determines the 95%-confidence interval: $WTP\ (mean) \pm 1{,}96 * \frac{\sigma_{Reliability}}{\beta_{Cost}}$ (Sillano & Ortúzar, 2003. Table 8.8 displays the upper and lower level of de confidentiality interval.

Table 8.8 - 95%-confidence interval WTP estimates

Reliability attributes	**Mean**	**Upper level**	**Lower level**
Reduce time with constraints with 1 hour	€0,60 per year	-	-
Increase indoor temperature with 1°C	€31 per year	€68	-€6
All rooms heated instead of 1 room	€30 per year	€112	-€36
Three rooms heated instead of all rooms	€10 per year*	€47*	-€27*
** Insignificant on a 95% interval level*			

Table 8.8 shows that for every reliability attribute, the lower level in the confidence interval is negative. This sign is counter-intuitive. The parameter estimates follow the normal distribution, which probably

causes this counter-intuitive sign (see Chapter 7). The real distribution of the parameters is unknown. The negative WTP implies that households do not want to pay for the reliability attributes. For example, some households do not want to pay for increasing the indoor temperature by 1℃. This report uses a lower level of €0 per year for every reliability attribute since the sign is counter-intuitive and based on a normal distribution, while the exact distribution is unknown. Moreover, no additional conclusions can be drawn for this research based on negative WTP estimates compared to a WTP of zero.

Table 8.7 shows that, on average, the respondents have the highest WTP for increasing the number of rooms that are allowed to be heated from "one-room" to "three rooms." There is a WTP to heat three rooms instead of all rooms. Subsequently, the respondents seem to accept a reduction in the number of rooms heated since the respondents obtain utility when only three rooms are heated. However, the estimated parameter for "three rooms" is insignificant, and no conclusions on the population level can be drawn.

Households are, on average, willing to pay between around €30 per year to heat all rooms instead of one room. Table 8.7 and Table 8.8 shows that there is much heterogeneity in the WTP. Based on the upper level of the confidence interval, a much higher WTP is estimated to heat all rooms instead of one room. The cost reduction households obtain from not heating the bedroom (so one room) is estimated at €50-€80 per year (Milieu Centraal, 2020; Van der Wilt, 2019). Heating one room costs around €50-€80. Comparing the average WTP to heat all rooms instead of one room of €30 per year with the actual cost of heating only room (€50-€80 per year) suggests a significant gap between the WTP and the heating cost. Even the upper level of the confidence interval shows a gap between the WTP (€112) and the cost. There is a gap when the house consists of at least three to four rooms, which seems plausible to assume. Concludingly, there is a gap between the WTP and the cost of heating a specific number of rooms. This gap is found on a 95%-confidence interval. This gap will further increase when the cost of a new system used for heating will increase.

The average WTP for households to increase the indoor temperature by 1℃ is €31 per year. The cost of increasing the indoor temperature with 1℃ is around €80 - €100 per year (Milieu Centraal, 2020; Van der Wilt, 2019; Milieu Centraal, n.d.). Consequently, households are willing to pay less to increase their indoor temperature than they are currently doing. When considering the upper bound of the 95%-confidence interval, the average WTP is €68 per year. €68 is still below the cost of increasing the indoor temperature by 1℃. Concludingly, there is a gap between the average WTP and the cost of increasing the indoor temperature for 95% certainty. If grid operators and energy companies decide to implement a reliable hydrogen system based on the current regulations, the cost will increase compared to the current grid. Therefore, the gap between cost and WTP will become more significant.

Finally, on average, households are willing to pay €0,60 to reduce demand constraints with one hour. During periods with a minimum temperature of -12℃, a house uses around 1,3 m^3 of natural gas per hour. The current natural gas price is 0,814 €/m^3. Subsequently, the cost of using natural gas during periods with -12℃ is €1,06 per hour. Concludingly, the cost of using natural gas during these periods is in the range of the WTP for reducing the constraint with one hour. The expectation is that the price for hydrogen will be higher than the current natural gas price, especially during the transition phase. The households will pay for the cost of the design of a very reliable hydrogen system. Consequently, the cost to use hydrogen during peak demand will increase and probably exceed the average WTP of the consumers for reducing demand constraints with one hour.

Conclusion

Based on this research, there is already a small gap between the average WTP for reliability and the cost of the natural gas system. The expectation is that a hydrogen system will be more expensive than the current natural gas system, especially in the beginning. In the beginning, there are no infrastructure or generation facilities. The implementation of expensive hydrogen infrastructures on a local level will significantly increase the cost. The construction of an electrolyser serving demand until -7℃ instead of -12℃ can decrease the cost by 15%. The cost reduction caused by lowering the investment costs can decrease the gap between the WTP and the cost of heating. Cost reductions of 15% ensure that the gap between the WTP and the cost cannot be concluded on a 95% confidence interval. The research cannot state there is a gap with 95% certainty anymore.

If the current regulation forces the grid operators and energy companies to implement a hydrogen system that meets the current reliability regulation, the gap between the WTP of households and the cost of heating will further increase. The exact cost of a hydrogen system is unknown. There is still uncertainty about the deviation of the cost. For example, it is unknown whether every affiliate to the natural gas system will pay for the transition cost to a hydrogen system. Or if only inhabitants of the neighborhood connecting to hydrogen will pay to construct the hydrogen infrastructure. Therefore, this report cannot draw specific conclusions about the WTP for reliability and the cost for reliability in a hydrogen system.

8.3.2 Influence of explanatory factors on the Willingness To Pay for the reliability attributes

This section discusses and estimates the influence of several explanatory factors on the WTP for reliability. The factors have a significant interaction effect with the cost reduction attribute. Section 8.2 elaborates on these factors. The estimation of the parameter for “three rooms heated” is not significant. Therefore, the influence of the factors on the WTP of “three rooms heated” is not specified. Table 8.9 displays the interaction effects with the cost reduction attribute

Table 8.9 - Interaction effects calculated

	ML
Cost reduction (Beta_Cost)	0,0149
Insights in the gas use (Beta_CostIns)	-0,00209
Good quality of insulation of the house (Beta_CostIns2)	-0,00228
Acceptability of sustainable heating (Beta_CostSUS)	0,00160
Maintained indoor temperature (Beta_CostTempD)	-0,00263

Insights in gas use

Households with insight into their gas use are less sensitive to cost reductions than households without this insight. Households with insights are probably more aware of their energy use and know how to reduce their energy cost. This explanatory factor explains part of the heterogeneity for the sensitivity for the WTP estimates for the reliability attributes. Appendix L calculates and shows the exact influence of the insight in the gas used on the WTP for the different reliability estimates. At the moment, this research cannot draw any additional conclusions based on this factor and the WTP, other than that the factor explains part of the heterogeneity.

Insulation

Households living in houses that are well insulated are more sensitive to price reduction than households living in less insulated houses. Appendix L, Table L.2 shows the WTP estimations for households living in well-insulated and less-insulated houses. Primarily the houses that are not well insulated will be connected to the hydrogen infrastructure (see section 3.3 for explanation). Therefore, the WTP from households living in less insulated houses is essential when determining the level of reliability in a hydrogen system.

Based on the WTP estimates, it is clear that, on average, the households living in less insulated houses have a significantly higher WTP for reliability than households living in well-insulated houses. However, there is still a gap between the WTP and the cost of the current natural gas system, on a 95% confidence interval. The research can state the gap with 95% certainty.

Concludingly, when designing a futureproof hydrogen system, it is essential to keep in mind that the houses connected to the hydrogen grid will be less insulted and use more hydrogen to keep their house thermally comfortable. However, the cost already exceeds the WTP for households living in less insulated houses, which implies that the reliability cost of the hydrogen system should not increase too much. The estimation for households living in poorly insulated houses is not significant. Therefore, this research does not conclude the WTP of households living in poorly insulated houses.

The expectation of using sustainable heating

The expectation of using sustainable heating has a significant interaction effect with cost reduction. This effect is positive, which means that if households have a higher expectation of using sustainable heating, the average WTP is lower. Appendix L, Table L.3 shows the WTP estimations for households with different expectations to use hydrogen. The gap between the WTP and the cost will further increase when the household has a higher expectation of using sustainable heating.

The first neighbourhoods that shift from natural gas to hydrogen are willing to use sustainable heating. Currently, grid operators cannot force households to change their connection. Even if they can force households on a longer-term, still, a threshold of supporters is needed to change the infrastructure in a neighborhood. Combining implies that the first projects should start with different reliability regulations. The transition phase is expensive, especially if the system should be very reliable from day one. The results imply that households that are willing to use sustainable heating want to reduce the reliability of the system to ensure the system will not become too expensive.

Maintained indoor temperature

Finally, the maintained indoor temperature has a significant interaction effect with the cost reduction. Households that maintain a higher indoor temperature have a higher WTP for reliability. A higher maintained indoor temperature gives a smaller gap between the WTP and the cost. The results imply that households maintaining an average temperature between 19℃ and 20℃ have a small gap between the WTP and the cost. Moreover, households maintaining an indoor temperature of 20-21℃ have no gap between the WTP and the cost.

Furthermore, households that maintain an indoor temperature higher than 21℃ have a dislike for any cost reduction in exchange for lowering the level of reliability. Households maintaining a high indoor temperature (above 20℃) seem to like the level of reliability that the natural gas system guarantees. Households maintaining an indoor temperature below 20℃ consider the current system as too expensive and in terms of cost, too reliable.

The maintained indoor temperature explains part of the heterogeneity in sensitivity for the WTP estimates for the reliability attributes. Appendix L calculates and shows the exact influence of the maintained indoor temperature on the WTP. The preferred indoor temperature has no direct link with the usage of hydrogen. The direct link with the usage of hydrogen is present for insulation or the expectation of using hydrogen. Furthermore, the effect of influencing the indoor temperature on the WTP is not known. Even more, one cannot influence the preferred indoor temperature of other households. Therefore, only the following conclusions can be drawn. First, the maintained indoor temperature explains part of the heterogeneity in sensitivity for cost reduction. Second, the gap between the WTP and the cost significantly decreases when households prefer a higher indoor temperature.

8.4 Summary of main findings

- On average, Dutch households prefer the design of a hydrogen system with a lower level of reliability over the current natural gas system. However, for the preference of an alternative hydrogen design over the current system, there is a significant level of unobserved heterogeneity that cannot be explained by the variables added to the model.

- A system with a higher cost reduction leads to a higher utility of the alternative. Households also prefer a system with a higher maximum indoor temperature and a system that can heat more rooms than one. Overall, households dislike extended periods with constraints. The cost reduction and the indoor temperature influences the choice for an alternative hydrogen design the most. Households are heterogeneous about the utility they obtain from different levels of the maximum indoor temperature, the number of rooms heated, and the cost reduction.

- This report identifies a gap between the average WTP for reliability and the current cost of the natural gas system. The identified gap holds on a 95%-confidence interval. The expectation is that a hydrogen system will be more expensive than the current natural gas system, especially in the beginning. In the beginning, there are no infrastructure or generation facilities. The implementation of expensive hydrogen infrastructures on a local level will significantly increase the cost. The construction of an electrolyser serving demand until -7℃ instead of -12℃ can decrease the cost by 15%. The cost reduction caused by lowering the investment costs can decrease the gap between the WTP and the cost of heating. Cost reductions of 15% ensure that the gap between the WTP and the cost cannot be concluded on a 95% confidence interval. This research concludes there is a gap between the WTP and the cost of reliability for 95% certainty. If the current regulation forces the grid operators and energy companies to implement a hydrogen system that meets the current reliability regulation, the gap between the WTP of households and the cost of heating will further increase.

- Houses that are poorly insulated will primarily use hydrogen as heating fuel. For the usage of hydrogen insulation is not a precondition as it is for the electrification of housesThe results show that households living in less well-insulated houses have a higher WTP for reliability. However, for these households, there is still a gap between the WTP and the current cost of heating. Based on the results, it is essential to consider that the houses connected to the hydrogen grid will be less insulted and use more hydrogen to keep their house thermally comfortable. Nevertheless, even households living in houses that are not well-insulated have a lower WTP than the cost of the reliability services.

- Households' expectation of using sustainable heating significantly influences the WTP for reliability. Households that are expected to use sustainable heating are willing to disconnect their house from the natural gas grid and use sustainable heating as alternative. The gap between the WTP and the cost will further increase when the household has a higher expectation of using sustainable heating. The first neighbourhoods that shift from natural gas to hydrogen are willing to use sustainable heating. Currently, grid operators cannot force households to change their heating connections from natural gas to sustainable fuels. Furthermore, it is expected that in the future, a specific percentage of supporters is necessary to implement a hydrogen infrastructure. The transition phase is expensive, especially if the system should be very reliable from day one. The results imply that households willing to use sustainable heating prefer to reduce the reliability of the system they are using to ensure the system will not become too expensive. Therefore, it might be a possibility to make the reliability regulations for the beginning and transition phase less strict than the final regulations. The transition regulations can help the development of an affordable, reliable, and sustainable hydrogen grid.

9. Sensitivity analysis

This chapter explores the sensitivity of the choice model by performing a scenario study. Different scenarios are set up to consider the sensitivity of different attributes. The report determines the support levels of different designs by estimating the choice probabilities. The choice probability is the probability that households vote for a particular alternative. The choice probabilities can help to make policy recommendations about the future design of an alternative hydrogen system. First, section 8.1 presents the choice model. Section 8.2 displays different scenarios. Finally, section 8.3 will discuss the results of this analysis.

9.1 Discrete choice model

To predict the support of an alternative hydrogen design, it chosen to use the ML model without the explanatory factors, such as the attitudes. The explanatory factors should not be included in any policy recommendations. It is unknown how attitudes develop over time and whether changes in the explanatory factors influence the support levels. The explanatory factors cannot be predictors for the future. Only the ML model with the attributes is used. Table 9.1 shows the estimations of this ML model.

Table 9.1 - Model estimations sensitivity analysis

Name	Value	Std err	t-test	p-value
ASC_HYDROGEN	3,59	0,337	10,65	0,00
Beta_COST	0,0127	0,00111	4,85	0,00
Beta_ROOM1	-0,841	0,141	-5,97	0,00
Beta_ROOM2	0,142	0,128	1,11	0,27*
Beta_TEMP	0,490	0,0414	12,30	0,00
Beta_TIME	-0,0177	0,00453	-3,92	0,00
Sigma_COST	0,0132	0,00147	9,00	0,00
Sigma_Hydrogen	4,46	0,420	10,61	0,00
Sigma_ROOM1	1,16	0,180	6,42	0,00
Sigma_ROOM2	-0,729	0,180	-4,04	0,00
Sigma_TEMP	0,316	0,0338	9,34	0,00
**Not significant at a 95% significance level*				
Rho-Squared	0,449			
Final Log-likelihood	-1792,638			
LRS	2920,717			

The choice probabilities of the different alternatives are calculated by using the mixed logit probability function. This report uses the probability density function only to determine different scenarios. Therefore, the panel mixed logit is not an addition to this research. The following formula calculates the choice probability (Chorus, 2018; Train, 2002):

$$P_n(i) = \int_{\upsilon_n,\beta_n} \frac{e^{\beta'_n x_{ni_t t}}}{\sum_j e^{\beta'_n x_{njt}}} * f(\upsilon_n, \beta_n))d\upsilon_n d\beta_n$$

The parameters are normally distributed, so the average choice probabilities for R draws are estimated by (Train, 2002):

$$P_n(i) = \frac{1}{R} * \sum_{r=1}^{R} (\prod_{t=1}^{T} \frac{e^{\beta'_n x_{ni_t t}}}{\sum_j e^{\beta'_n x_{njt}}} | v_n, \beta_n)$$

The choice probabilities of the different alternatives (the two alternative hydrogen systems and the natural gas system) are based upon the different utility functions. The utility functions for the three alternatives are:

$$U_{Hydrogen1} = 0{,}951 + 0{,}00537 * CostA - 0{,}0177 * TimeA + 0{,}509 * TempA - 0{,}841 * RoomA1 + 0{,}142 RoomA2 + v_{Hydrogen}$$

$$U_{Hydrogen2} = 0{,}951 + 0{,}00537 * CostB - 0{,}0177 * TimeB + 0{,}509 * TempB - 0{,}841 * RoomB1 + 0{,}142\ RoomB2 + v_{Hydrogen}$$

$$U_{Naturalgas} = 0{,}00537 * CostC - 0{,}0177 * TimeC + 0{,}509 * TempC - 0{,}841 * RoomC1 + 0{,}142\ RoomC2$$

The random parameters for the hydrogen taste parameter and the parameters of the cost reduction, indoor temperature, and amount of rooms heated are normally distributed by:

$v_{Hydrogen} \sim N(0\,; 4.46)$

$\beta_{Cost} \sim N(0.00537\,; 0.0132)$

$\beta_{Temp} \sim N(0.509\,; 0.316)$

$\beta_{Room1} \sim N(-0.841\,; 1.16)$

$\beta_{Room2} \sim N(0.142; 0.729)$

9.2 Scenarios of the alternative hydrogen design

This section discusses different scenarios for the design of an alternative hydrogen system. The support for these designs will be predicted based on the choice probabilities. The design of the hydrogen system will differ based on the amount of cost reduction, the maintained indoor temperature, and the time constraint. It was chosen not to vary the number of rooms heated since the estimate for "three rooms heated" was not significant. Moreover, there is a general dislike for a system with only "one-room heated."

There is a positive value for the alternative specific constant is the estimated model. On average, there is a preference for an alternative hydrogen design. A base scenario or reference scenario is made to determine the support for different hydrogen alternatives. The reference scenario will be a scenario in which the hydrogen alternative has the same level of reliability as the natural gas system. The cost reduction is zero, the maximum indoor temperature is 23°C (which is assumed to be maximal in this research), there is no time with demand constraints, and all rooms are allowed to be heated. Beneath different scenarios are made to understand the trade-off between the cost and the level of reliability between two hydrogen systems. The different scenarios identify the impact of different changes in the reliability and affordability of the hydrogen system based on the choice probability.

9.2.1 Base scenario

The hydrogen system, with an equal level of reliability, has a higher choice probability than the natural gas system, due to the general like for a hydrogen system. Table 9.2 displays the reference scenario. The other scenarios in this chapter will be compared to the reference scenario.

Table 9.2 - Hydrogen system in the base scenario

Attributes	Attribute levels
Cost reduction	€0 per year
Time with demand constraint	0 hours/year
Maximum indoor temperature	23°C
Amount of rooms heated	All rooms

9.2.2 Scenario 1 – Minimizing cost

In the first scenario, the cost of the hydrogen design is kept low. The affordability goal is the primary goal for the design of a hydrogen system. The level of reliability is low since affordable generating facilities are built. These facilities have not much generation capacity. Yearly, 29 hours with demand constraints hold during which the maximum indoor temperature is 17°C. All rooms are allowed to be heated. Table 9.3 displays the scenario.

Table 9.3 - Hydrogen system in scenario 1

Attributes	Attribute levels
Cost reduction	€210 per year
Time with demand constraint	29 hours/year
Maximum indoor temperature	17°C
Amount of rooms heated	All rooms

Based on the choice probability, this scenario has a support level of 31%, while the support level of the reference scenario is 69%. The high amount of cost reduction in combination with a shallow level of reliability results that there is less support for this system. Only the cost reduction attribute causes that the utility of this system increases. The lower indoor temperature and the more extended period with demand constraints create a decrease in utility. The decrease in utility implies that the affordability goal needs to be considered in combination with reliability. By increasing the annual cost reduction to €273 gives a support level of 50%.

9.2.3 Scenario 2 – Average in affordability and reliability

The second scenario slightly decreases the level of reliability and cost. The maximum indoor temperature during constraints is 20°C. Every year around 10 hours with demand constraints exist. Finally, the cost reduction created by the system with a lower level of reliability is €145 per year, based at an electrolyzer that serves demand till -7°C. Table 9.4 shows the chosen attribute levels.

Table 9.4 - Hydrogen system in scenario 2

Attributes	**Attribute levels**
Cost reduction	€145 per year
Time with demand constraint	10 hours/year
Maximum indoor temperature	20°C
Amount of rooms heated	All rooms

The support level of this scenario is 55%, while the base scenario has a support level of 45%. The support level implies that a reduction in reliability and cost gives a higher support level for the hydrogen alternative. More utility is obtained from the higher cost reduction in this alternative, while the utility compared to the reference scenario decreased by the maximum temperature and the time with constraints. This scenario creates a support level of 50% when the system has a cost reduction of €130 per year.

9.2.4 Scenario 3 – A long period with constraints

The third scenario designs a hydrogen system with a reduced level of reliability with lower costs. The period with demand constraints is 29 hours per year. During this demand constraints, households can maintain an indoor temperature of 21°C in all rooms. The cost reduction created in this system equals €80 per year. Table 9.5 displays the attributes of this scenario.

Table 9.5 - Hydrogen system in scenario 3

Attributes	**Attribute levels**
Cost reduction	€80 per year
Time with demand constraint	29 hours/year
Maximum indoor temperature	21°C
Amount of rooms heated	All rooms

The identified system has a support level of 38%, while the reference scenario has a support level of 62%. Households do not prefer an extended period with demand constraints even if they can maintain a higher indoor temperature. A cost reduction of €80 per year increases the utility of the system, but not enough to compensate for the utility reduction due to the demand constraints. In case a cost reduction of €117 per year is achieved, the support for both systems is 50/50. A cost reduction of €145 for this system implies a support level of 59% (against 41%).

9.2.5 Scenario 4 – Short but constrained

The fourth scenario displays a system with only a short period with a demand constraint, but the demand constraints are low. The maximum indoor temperature is 18°C for 3 hours per year. The cost reduction for this system is €210 per year. Table 9.6 displays the attribute levels for this scenario.

Table 9.6 - Hydrogen system in scenario 4

Attributes	**Attribute levels**
Cost reduction	€210 per year
Time with demand constraint	3 hours/year
Maximum indoor temperature	18°C
Amount of rooms heated	All rooms

The support level of this system equals 54%, while the support level of the reference system equals 46%. For more than half of the households, the cost reduction compensates for the increase of the period with demand constraints and the low indoor temperature during this constraint. When increasing the indoor temperature by 1°C to 19°C creates a support level of 66%.

9.2.6 Scenario 5 – High support level

The fifth scenario searches for a support level that equals 80%. The importance of the attributes "cost reduction" and "indoor temperature" are considered to be most important for choosing an alternative hydrogen design. The period with constraints 10 hours per year. The cost reduction is €200 per year, and the maximum indoor temperature during times with constraints is 21°C. This scenario gives a support level of 80% over de hydrogen system with the current reliability regulations. Furthermore, when decreasing the maximum indoor temperature during demand constraints by 1°C to 20°C, the cost reduction should be €240 per year to achieve a support level of 80%.

9.3 Conclusion

Based on the findings of the model application, one can state that affordability and reliability should be considered together. Households have the most support for hydrogen systems with a lower level of reliability and cost. Striving for a reliable system should not be a goal on its own, as is the case in the current system used for heating. However, there should be a significant cost reduction to lower the level of reliability by lowering the indoor temperature or increasing the period with more demand constraints. Also, Affordability should not be the aim of energy systems. It is essential to consider the reliability and affordability of the design of the hydrogen system.

10. Discussion and reflection

This section discusses the contribution of this research. First, section 10.1 elaborates on the scientific contribution. Section 10.2 discusses the practical and social contributions of this thesis. Finally, section 10.3 considers the recommendations for further research and the reflection of the research.

10.1 Scientific contribution

The primary scientific contribution of this research is the assessment of the trade-off between the reliability and affordability of an energy system from the households' perspective. The analysis of this particular trade-off has never been the subject of discussion. The system used for heating has reliability regulations. Based on these reliability regulations, the cost of the energy infrastructure is determined. The reliability has never been weighted to the affordability goal, especially not from the households' perspective. This research provides insights into the preferences of the households in the trade-off between a reliable and affordable energy system. Moreover, this research quantifies the households' Willingness To Pay (WTP) for energy systems.

The hydrogen system used for heating is a common pool resource. The households cannot be excluded from the use of hydrogen, and the consumption of hydrogen is rival. A challenge of a common pool resource is the fair distribution of the cost and benefits across the households (Gill, et al., 2017). The optimum between reliability and affordability is hard to find in common-pool resources. The households should transfer the efforts taken for a reliable hydrogen system into benefits to create an economically efficient system—a higher benefit from a service such as reliability results in a higher Willingness To Pay (WTP) for reliability. Grid operators, such as Stedin, are responsible for the distribution of hydrogen, while the energy companies are responsible for the generation of hydrogen. There is no one on one relationship between the investment costs of the grid operators and energy companies and the benefits of the households. The investment costs should not outreach the WTP for the households. The WTP for a more reliable energy service decreases when the utility of the user will no longer increase due to better services.

A higher level of reliability increases the cost (CPB, 2014; Brown, et al., 1997). The total cost line in Figure 10.1 shows this relation. This research shows that investments in the natural gas system are not economically efficient—the cost of reliability outreach the average WTP for reliability by the Dutch households. Households do not transfer the efforts taken to create a very reliable natural gas grid into benefits. The natural gas grid is not in optimum between the reliability and cost. The cost does not display the benefit. The relationship between the cost and reliability of the natural gas system is in the blue striped rectangle in Figure 10.1. The cost and level of reliability are higher than the optimum shown by the green line.

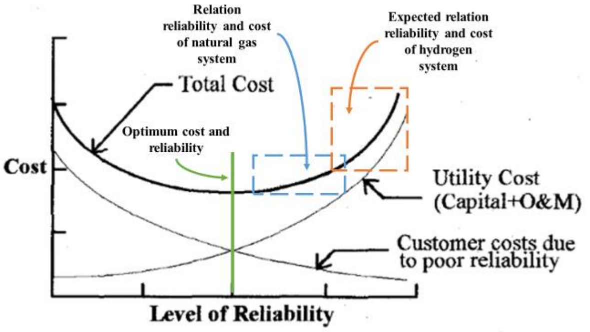

Figure 10.1 - [Reliability Cost Curves natural gas system and hydrogen system]. Retrieved from: Brown, et al., 1997. [Online Image]

Implementing a hydrogen system will be more expensive than the current cost of the natural gas infrastructure. Especially the cost of reliability will increase. Therefore, the cost and reliability need to decrease to create an economically efficient hydrogen system. If the current reliability regulations are guaranteed, this research expects that the relationship between cost and reliability in a hydrogen system will be visualized by the orange striped square in Figure 10.1. Concludingly, there is no optimum between cost and reliability.

The level of reliability must be reduced to create an optimum between the cost and the reliability (green line in Figure 10.1). The hydrogen system is a common-pool resource and has rival and non-excludable characteristics. Common-pool resources must have access regulations due to these characteristics. When adjusting the level of reliability, new access regulations have to be created, especially during scarcity. During scarcity, hydrogen will be rival since one household cannot use the hydrogen used by another household (Künneke & Finger, 2009; Ostrom, et al., 1999). Stedin, as a grid operator, is responsible for maintaining a reliable and affordable system used for heating. The next section gives recommendations about excess regulations for Stedin.

Even though striving for a reliable energy system is an important goal, it is essential to determine the WTP for this level of reliability. The WTP for reliability usually decreases when the utility derived from better services no longer increases. The investigation of Gill, et al. (2017) stated that a higher WTP for reliability in energy systems is obtained by a higher utility or benefit derived from service. This research also founded this relation. This research found that the WTP for reliability increases when households maintain a higher indoor temperature. These households need more energy to fulfill the preference, namely a higher indoor temperature. Also, households living in less-well insulated houses have a higher WTP for reliability. These households need more energy to keep their houses warm than households living in well-insulated houses.

The reliability of energy systems “reflects the ability of the system to deliver the product (or service) transported over the network without interruption and deterioration of its quality” (CPB, 2004). The report of Shrivastava, et al. (2009) defines reliability as the “ability to maintain and execute error-free operations.” The reliability of the gas system is mainly seen as the continuous delivery of natural gas at all times. Based on this definition, it is striking that the choice of households for a preferred system used for heating is least influenced by the time with demand constraints. This finding implies that households think continuous delivery is less important than the quantity (and quality) of gas that is delivered. Therefore, the definition of the reliability in the gas system from a consumer perspective found in this research is most in line with the definition of reliability given by McCarthly, et al. (2007). This report described reliability as “the ability to supply the quantity and quality of energy desired by the customer when it is needed.” This definition displays the importance of the quantity of gas as is desired by the households.

In the electricity domain, the incorporation of the preferences of households led to a different design of the system. It became apparent that the affordability goal is essential, and that reliability should not be a goal on its’own (Billimoria & Poudineh, 2019; Swalehe & Marunghri, 2018). Different studies showed that households are sensitive to cost reductions and are willing to change their demand patterns due to economic incentives. Households are willing to shift their demand from peak hours to off-peak hours. The changing demand patterns caused a reduction in the capacity of transportation and generation facilities (Billimoria & Poudineh, 2019; Swalehe & Marunghri, 2018).

The electricity domain is different from the heating domain since peak demand cannot be shifted as easily in systems used for heating. However, this research shows that households are sensitive to cost reductions in the heating domain and are willing to change their demand patterns. This research shows that incorporating the preferences of households leads to different system designs. The outcomes show that the affordability of the system is a vital goal next to sustainability and reliability. This research concludes that next to the electricity domain, also the heating domain should consider the demand when designing a future proof system.

When considering innovation, different kinds of adaptors can be distinguished. A commonly used innovation theory of Rogers (2003) identifies five different groups of adaptors: innovators, early adopters, early majority, late majority, and laggards. Innovators and early adopters are less concerned about problems and want to test new technologies. In this research, an hydrogen system is an innovation, with adaptors, followers, and laggards. The division of the groups of adaptors can be made upon attitudes towards sustainable heating. The attitudes towards sustainable energy are seen as an essential condition to create the energy transition (Hansla, et al., 2009). The willingness to participate in the energy transition and make sure the built environment switches from natural gas to a sustainable alternative is a necessary condition to induce change (SCP, 2020). This research found a strong correlation between households with a high expectation of using sustainable heating with the preference for a hydrogen system with another level of reliability. These households are the frontrunners of a hydrogen infrastructure and want to make the built environment sustainable. They are less concerned with problems related to lowering the level of reliability. They probably see the reduced reliability as a precondition for implementing the hydrogen system.

Lastly, this research looks into the trade-off between affordability and reliability of a hydrogen system from a consumer perspective for a hydrogen system. The results show that reliability should not be a goal on its own. The current natural gas system is too expensive. The cost for the reliability services of the natural gas grid exceeds the WTP for the reliability of the households. Therefore, the system is over reliable in terms of cost. For the implementation of a sustainable alternative, reliability should be considered with affordability. The conducted choice experiment included hydrogen, instead of other sustainable heating alternatives. It is not known what the influence of hydrogen is on the outcome of this research. However, the results indicate the importance of starting the discussion to reduce the level of reliability for a hydrogen system. This research shows that it is crucial to determine the trade-off from households between reliability and affordability in other systems used for heating, such as electrification, heating grids, or the use of green gas as well.

10.2 Societal contribution

This research gives insights into the preferences of the households in the trade-off between reliable and affordable energy systems. The households are the users and the payers of the system. The preferences of households are essential when designing a desired and future proof energy system. Currently, there is a natural gas system with predefined reliability regulations. These regulations were defined years ago, during the rollout of the natural gas system. The government set up these regulations without the assessment of the preference of the households.

Stedin is responsible for distributing energy and has an essential role in creating a sustainable built environment. Stedin will become more involved in the match between supply and demand, especially in regional clusters. The Gaswet regulates the reliability in the grid and states that there should always be enough supply to meet demand until -12°C.

GTS (Gasunie Transport Services) is responsible for the balancing of supply and demand. In the future, grid operators will probably also get the task of balancing the grid. Sustainable energy will enter the grid in more and local points instead of only in a few national points. The grid operators will become independent actors that match the supply and demand. Moreover, grid operators must ensure that the interests of households will be guaranteed. The grid operators must guarantee an affordable and reliable system that delivers energy to the households.

In the coming years, the housing stock needs to become sustainable. Therefore, the design of new sustainable systems used for heating is necessary. The public service task of Stedin (and the other grid operators) is to define a system that is reliable and affordable. A high level of reliability results in high costs of the system and higher energy bills for households. This research shows that households do not desire the costly and reliable grid based on the current regulations. The households are not willing to pay for the costs of the reliability services of the current system. In terms of cost, it seems that households consider the system as over reliable. Therefore, it is vital to consider other possibilities to match the supply and demand for a new hydrogen system. There are other possibilities to create a reliable system. These possibilities eliminate the need to over-dimension the generation capacity that meets demand in extreme conditions.

The cost of the hydrogen system significantly decreases when the Government decides to ease the reliability regulations. When the regulations apply a minimum 24-hours temperature of -7°C instead of -12°C, the construction cost can be decreased by 15%. The current reliability regulations cause high service costs, which will further increase in a hydrogen system. The households do not desire the high cost and prefer to reduce the level of reliability in exchange for money slightly. Concludingly the regulations are too strict from the households' perspective.

The government based the reliability regulations on the weather of almost 60 years ago. The weather conditions have changed significantly. This research looked at the weather data in "De Bilt," since De Bilt is the yardstick for the weather in The Netherlands and is the head location of the KNMI. De Bilt is located at the center of The Netherlands, where the most average temperatures are measured. Based on the weather data of "De Bilt," one can see that in the last 20 years, no cold period came close to a minimal 24-hours temperature of -12°C. Even a 24-hours temperature of -7°C did not occur in the last 20 years. An electrolyser that meets demand until -7°C compared to -12°C reduces the investment cost by 15%. Reducing the cost of the system decreases the gap between the WTP and the cost. When decreasing the cost by 15%, the gap cannot be stated on a 95% confidence level anymore. Decreasing the cost by 15% results in the possibility there is no gap between the WTP and the cost.

Next to national reliability regulations, the design of regional reliability regulations will be appropriate at the beginning of the energy transition. In the coming years, Stedin will disconnect neighbourhoods from natural gas to create a sustainable energy infrastructure. The transition will start on a local or regional level. Figure 10.2 shows the average lowest temperature in The Netherlands in the coldest months. From this figure, one can conclude that the regions closer to the sea have higher winter temperatures than the regions in the east of The Netherlands. Furthermore, the regions will have a different temperature than is measured in De Bilt.

The minimum outside temperatures significantly influence the demand for hydrogen. The minimum temperature differs per region, and the design of the hydrogen will start at a local level. Therefore, for the hydrogen projects in the coming years, regional reliability regulations should be designed. Why design a hydrogen system nearby the coast on the colder extreme temperature in the east?

Moreover, it is likely to determine the national reliability regulations on the weather data of De Bilt, since this location is the yardstick of the weather. Moreover, The Bilt is located in the middle of The Netherlands and can give appropriate measures of the average temperature. However, a regional project, designed on the weather data of De Bilt, will make no sense. The location can either have colder periods or warmer periods, which causes different demand patterns. In 2050, The Netherlands will probably have a national hydrogen grid. This grid can reduce shortages on the local levels. However, for the coming years, regional reliability regulations will result in infrastructures designed for the specific location and may reduce the cost of the energy transition.

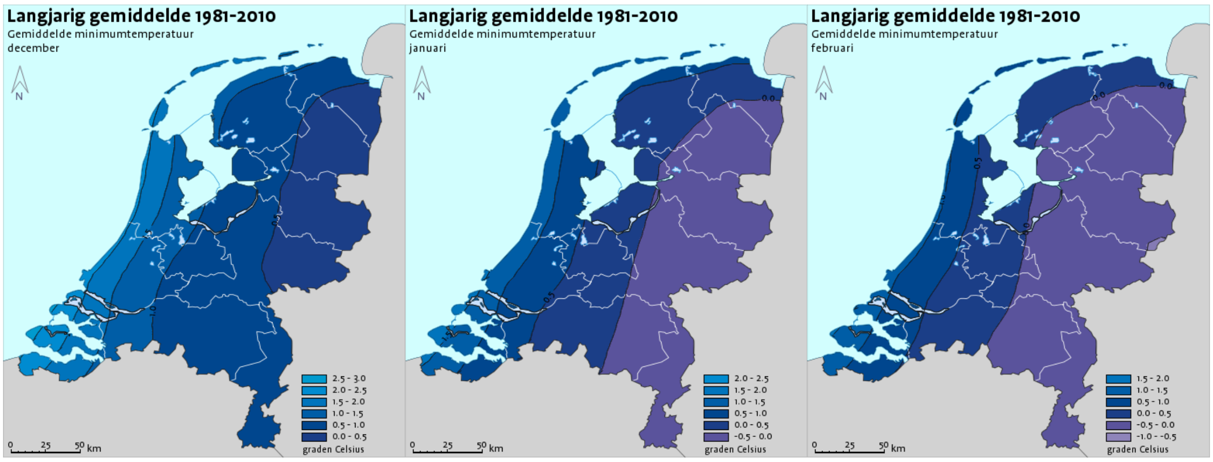

Figure 10.2 - Regional temperatures December, January and February

The use of transition regulations is supported by the fact households who indicated that they are expecting to use sustainable heating have a strong preference for a hydrogen system with a reduced level of reliability. Due to the current legislation, grid operators cannot force households to change their heating connection to the hydrogen system. Stedin expects that in the future, a certain percentage of inhabitants should be willing to change their heating connection before a sustainable system used for heating can be implemented. If inhabitants of the neighbourhood do not support the transition, it is hard to accomplish a transition.

The transition phase to hydrogen will be expensive, especially if the system must be very reliable from day one. The previous paragraph pointed out that households living in neighbourhoods that, in the coming years, will be connected to a hydrogen system prefer a hydrogen system with a lower level of reliability. Therefore, the possibility to implement transition regulations should be considered. Less strict transition regulations can ensure an affordable hydrogen system, while demand can create a more reliable hydrogen system. Frontrunners seem willing to reduce their demand during peak hours, creating flexible demand in the coming years.

Within the coming years, grid operators will extend the hydrogen infrastructure. Stedin, as well as literature, expects that in the longer term, there will be a national hydrogen grid and that hydrogen can be imported from abroad. In the end, the national grid will absorb the shortages on a local level. Transition regulations that focus on the regional character of the transition and the preferences of the first participants of the energy transition can create a reliable and affordable hydrogen system.

The reliability regulations are the framework of the match between supply and demand. If The Netherlands decides to implement less strict reliability regulations, the match between supply and demand will need more emphasis.

On the supply side, there are different possibilities to create a reliable grid. The first is the construction of generation capacity that generates enough hydrogen until a predefined extreme temperature, the reliability regulation. A way to reduce the generation capacity is by creating local storage facilities. The storage facilities can deliver hydrogen during shortages and ensure that energy companies can construct lower generation facilities. The disadvantage of local storage facilities is, however, the cost. The cost of local storage facilities can exceed the cost of constructing larger electrolysers. Local storage facilities are expensive since the hydrogen must be stored at high pressure and for a long time. The hydrogen will only be used during extreme periods.

Another possibility on the supply side to decrease the generation capacity of electrolysers is the transport of hydrogen by trucks during shortages. Usually, a period of low temperatures is predictable. Before the cold period, the overcapacity of electrolysers can be used to fill the trucks with hydrogen. These trucks can transport the hydrogen to the regions with a shortage. When using trucks, it is essential to create contracts about the delivery and storage of hydrogen and ensure sufficient truck capacity to overcome the shortage. Figure 10.3 visualize the possibilities on the supply side.

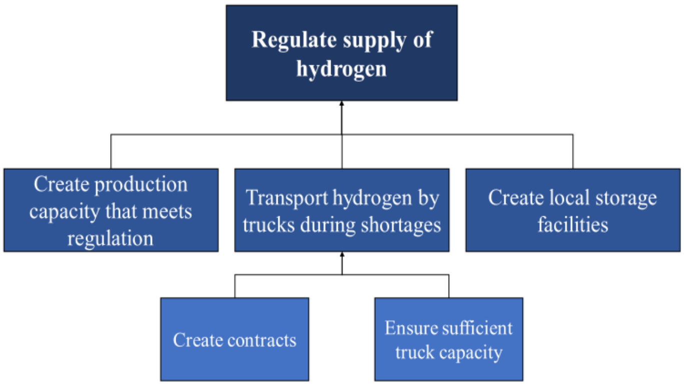

Figure 10.3 – Regulation of the supply of hydrogen

Lastly, adjusting the demand for hydrogen can help to make the system less reliant on the supply of hydrogen and to make the system more affordable. A way to adjust the demand for hydrogen is by reducing the demand of households during peak hours. It is almost impossible to restrict the hydrogen use of households due to EU codes. The households are protected from the restriction of energy. The demand can be reduced by stimulating households to use less hydrogen during peak hours. This research proved that giving households a cost reduction is a proper way to reduce hydrogen demand. Households are sensitive to cost reductions and are willing to change their demand in exchange for financial incentives.

Another way to stimulate households to use less hydrogen during peak hours is by setting up contracts. These contracts include fees and financial compensation for reducing the demand. Grid operators can use fees to ensure that households use not more hydrogen than agreed during peak hours. Grid operators can give financial compensation for reducing their demand, so less supply is needed. Grid operators can use financial incentives together with contracts to incentivize households to reduce their demand during peak hours.

Alternatively, grid operators can reduce the demand of households during peak hours by implementing a technical constraint in the distribution infrastructure. This technical constraint can constraint the hydrogen distributed to houses until, for example, 1 m^3 per hour. In this way, a household cannot use a lot more hydrogen at the expense of another household during shortages. Finally, grid operators can ensure that the households install advantaged hydrogen conversion systems. A hybrid heating pump or boilers running on hydrogen can spread the demand during peak hours. All three ways can be used together to reduce the demand of households during peak hours. See figure 10.4 for the visualization.

Another way of reducing the demand for hydrogen during shortages is by disconnecting or restricting the hydrogen usage of large energy consumers. Restricting or disconnecting large consumers of hydrogen can make sure enough hydrogen capacity remains available during shortages. Ways to restrict or disconnect large consumers is by setting up contracts and the design of technical constraints. The contracts should make it attractive for large consumers to collaborate and reduce or stop their hydrogen demand. Furthermore, fees should prevent large consumers from using more hydrogen than agreed. The technical constraints can ensure the large consumer can only use a specific amount of hydrogen during shortages or to disconnect the user during periods with shortages from the hydrogen infrastructure completely. Grid operators can use technical constraints together with contracts. Figure 10.3 visualizes the options on the demand side.

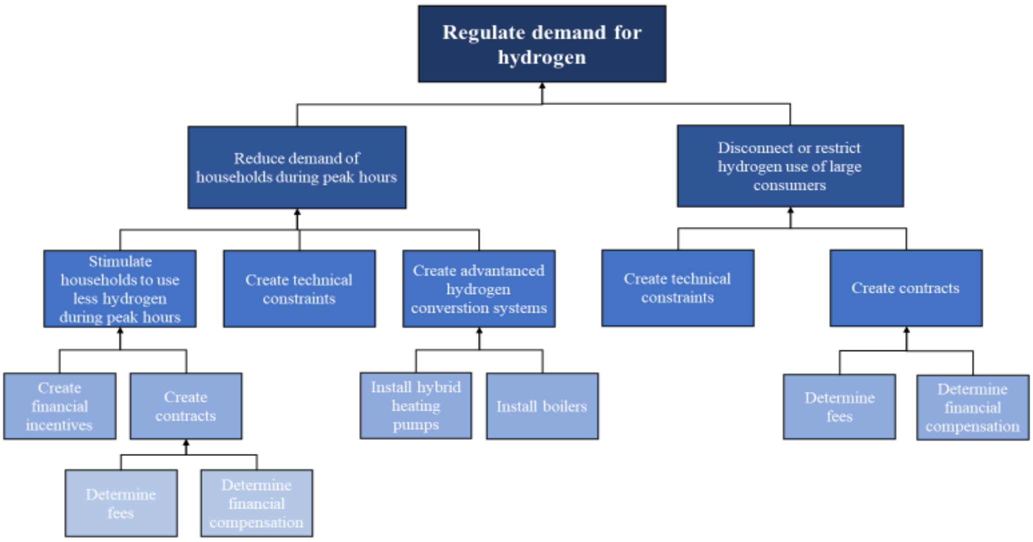

Figure 10.4 – Regulation of demand for hydrogen

It is expected that the demand for hydrogen will change compared to the demand for natural gas. The cost of hydrogen will be higher than natural gas. Households are sensitive to price developments. Therefore, it is likely that the demand for hydrogen will be lower than the current demand for natural gas. However, since this is only an expectation, and grid operators cannot steer it, this research will not further consider this demand change.

Considering the options on the supply and demand side can create a match between supply and demand in a more affordable way. The reliability regulations should consider the different possibilities that grid operators can take to match supply and demand. It is unnecessary to create a system that guarantees reliability until the current extreme circumstances. By using the buttons available, grid operators can design a reliable and affordable infrastructure. Stedin is not able to reorganize all the options mentioned in this section. The next Chapter will give specific recommendations for Stedin.

The consideration of demand in the design of the system is a point of discussion. The wishes and attitudes of households related to reliability will likely change over time. Suppose that in the coming decades, there will be a very cold period through which the demand will increase significantly, and households do not care about the price for hydrogen. In this scenario, the system must be reconsidered and probably extended. Therefore, it is crucial not to determine the system design only on the wishes of the households. Grid operators must design a future proof system. However, the wishes of the households can give space to the affordable implementation of a hydrogen grid that considers the demand flexibility.

10.3 Reflection

The first shortcoming of this research is that the sample of the Dutch population that filled in the survey was not representative. Also, the mediums to spread the data may have led to biases. Many co-workers from Stedin filled in the survey. Probably the employees of a grid operator are more biased in their choice of a hydrogen system used for heating. The representativity of the sample was tested based on gender, age, income, and educational level. The sample turned out to be insignificant in all these aspects. The expectation is that because the sample is unrepresentative, another sample may lead to different outcomes.

Furthermore, self-selection may have occurred. Respondents were free to fill in the survey, which results that households with an opinion about the subject are more likely to fill in the survey. Moreover, the survey was spread by a link put on the customer satisfaction survey of Stedin, which may have led to more self-selection.

Another bias likely to occur in choice experiments is the hypothetical bias. The researcher is never sure whether the choices made in the survey are the same as in real life. There are no real consequences to the choices. The parameters could be overestimated since the respondents may be too optimistic about their valuation of an alternative hydrogen system. The introduction of the survey states that the outcome of the research is used for the decision making of the future hydrogen system to limit the hypothetical bias. However, it is unknown to what extent hypothetical biases have occurred in this research. The influence of this bias on the WTP and preference for a system with a lower level of reliability is unknown.

Based on the outcomes of the research, a reflection can be given about the attribute (levels) and alternatives used in the stated choice experiment. The use of only "one heated room" during demand constraints is too low. The use of "two heated rooms" as the lowest level of the attribute may have given more useful outcomes. Also, the attribute level "three heated rooms" turned out to be insignificant. Nevertheless, on the sample level, the conclusion can be drawn that a small utility is obtained by heating "three rooms" over "all rooms." In the natural gas system, all rooms are always heated. The expectation is that the utility obtained between "three rooms" and "all rooms" is caused by the utility obtained from a sustainable hydrogen system. This utility raises attention to the reflection of the construction of the alternatives in the choice experiment.

In the choice experiment, the respondents had to choose between two hydrogen alternatives and the current natural gas grid. However, more about the trade-off between reliability and affordability could be given if the alternatives all consisted of the same heating fuel. In this research, the trade-off is two-fold. First, is the respondent willing to choose a hydrogen alternative over a natural gas alternative? Second, does the respondent prefer a hydrogen system used for heating with a lower level of reliability in exchange for a cost reduction? The natural gas system is added to the experiment to ensure that respondents are not forced to choose a hydrogen alternative. Currently, it is not possible to force households to change their heating connection. Therefore, it is not realistic to force respondents to make this decision. Due to the exploratory character of this research, the two-fold trade-off is expected not to be a problem. However, for more information about the trade-off from the households' perspective, it is essential to ensure the trade-off is one-sided.

In this research, 20% of the respondents showed non-trading behavior. Non-trading behavior has different drivers. A driver could be that respondents have a strong preference for a specific alternative. In this case, the respondent still optimizes his/her utility (Hess, et al. 2010). Other drivers can be non-utility maximization drivers, such as the choice due to boredom or the difficulty of the choices. It can also be that a respondent is strategically or politically motivated. In this case, the respondent does not maximize his/her utility either (Hess, et al., 2010). It is best to remove the non-trading drivers that do not maximize the utility from the data set, to avoid biases in the parameter estimates and the Willingness To Pay (WTP) estimates (Hess, et al. 2010). However, it is almost impossible to recognize the drivers based on the data. In total, 78 of the respondents always choose the natural gas alternative, three respondents always choose sustainable hydrogen alternative one, and three respondents always choose sustainable hydrogen alternative two.

Based on the literature, there would be a significant amount of respondents that would always choose a natural gas system. There is a group that has a strong preference for maintaining the current heating fuel or maintaining the current level of reliability and cost. Since it is expected that part of the population has a strong preference for maintaining the current situation, this group should be represented in the sample (Ahlheim & Neidhardt, 2010). The amount of respondents that always choose to maintain the natural gas system is 19%. SCP (2020) found out that around 27% of the households do not support a gas-free policy in the built environment. Concluding, 20% seems like an appropriate percentage that reflects the number of households that want to maintain the current situation.

Furthermore, six respondents always choose the same sustainable hydrogen alternative. The drivers for this group of non-traders are not known. However, since 6 out of 411 is only 1%, it is assumed that this will not have severe implications for the parameter estimates and the WTP estimates. The non-traders were not excluded since it was assumed that the removal of the non-traders would lead to biased estimates as well (Ahlheim & Neidhardt, 2010). However, since the exact drivers for the non-trading behavior are unknown, this aspect needs to be reconsidered in further research.

Another limitation of this research is that there is a significant amount of unobserved heterogeneity. The unobserved heterogeneity implies that the attributes do not explain all the factors that households make when choosing a system used for heating. The amount of unobserved heterogeneity relates to a commonly mentioned limitation of stated choice experiments. It is plausible to assume that households consider more attributes when deciding for a system used for heating than are considered in the stated choice experiment. For further research, it is recommended to do more qualitative research to investigate what aspects of energy systems the households find essential. It is crucial to create a better understanding of the benefit of a reliable energy system from the perspective of households.

Additionally, to the limitations mentioned above, it is essential to note that this research assumed that the attributes are normally distributed, while the exact distribution is unknown. The use of normal distributions can give counter-intuitive signs, which were also found in this research. Further research should consider other distributions, such as the triangular or the truncate of the normal distribution.

Lastly, the period of the conduction of the research should be considered. The survey is distributed in summer, and it is reasonable to assume that respondents are more optimistic about reducing their gas use compared to winter. In summer, the households in the Netherlands rarely use their thermostats. Furthermore, it is essential to consider that due to the COVID-19 crisis, households are more often at home. Households will experience the downsides of a less reliable system more than when they are away from home more often, which may lead to too negative estimations of parameters.

11. Conclusion and recommendations

This chapter first discusses the conclusion of the research in section 11.1 by answering the different sub-questions as well as the research question. Section 11.2 elaborates on scientific recommendations and recommendations for Stedin related to this research. The conclusions are based on a literature study and 411 surbey responses.

11.1 Conclusion

This section will answer all the sub-questions. Section 2.5 and 3.4 already answer the first two sub-questions. Therefore, these questions are touched upon briefly while thoroughly discussing the three sub-questions related to data analysis and the final research question.

1. What characterizes the relationship between the cost and reliability of energy systems?

Energy systems are common-pool resources, which causes no one to one relationship between the investment cost of the grid operators and energy companies and benefits for households. Increasing the level of reliability in energy systems comes with higher costs, especially since the last part of creating a 100% reliable energy system is very costly. Reliable energy systems deliver the quantity and quality of energy desired by the households. Based on the predefined rules of the ACM, the grid operators have to maintain the agreed level of reliability in the grid. Therefore, grid operators need to make investments in the energy system. Households are users of the system; they obtain the benefit of reliable energy systems and need to pay for the systems. The benefit or utility obtained from a reliable energy system determines the Willingness To Pay (WTP) for the reliability of households. Different factors influence the utility obtained from reliability and, in addition to that, the WTP for reliability.

2. What are the most important technical options to create a design with a reduced level of reliability of a green hydrogen network used for heating?

If grid operators implement a design with a lower level of reliability, they must guarantee that every affiliate receives the same amount of hydrogen. Grid operators have to distribute the hydrogen equally during shortages. Therefore, measures should be taken. A possible way to reduce the amount of hydrogen transported to individual houses during shortages will be to set up contracts. The contracts will include financial compensation and fines. The fines will be given to households that did not hold to their agreements and used more gas than agreed. The result of such a breach of contract imposes the possibility of interruptions in the system, causing others not being able to heat their homes. Whether fines will work is a point of discussion due to negative side effects of imposing fines. Financial incentives can stimulate households to decrease their demand during peak hours. However, this measure cannot ensure the hydrogen is distributed equally and can only reduce the peak demand if households are sensitive to cost reductions given in the heating domain.

Another way to ensure every affiliate receives the same amount of hydrogen could be by implementing technical constraints in the distribution grid. Technical constraints ensure that households do not use more hydrogen than agreed, by limiting the distribution. Finally, the hydrogen demand can also be changed by using different hydrogen conversion systems inside the houses. When grid operators install a hybrid heating pump or a boiler, the hydrogen use is more spread in time. Spreading the demand results in less peak demand.

The reliability of the hydrogen system primarily influences the investment costs. Literature expects that the variable production cost of hydrogen in the long term can become compatible with natural gas. Furthermore, it is expected that a high level of reliability does not significantly influence the transportation cost of hydrogen. The gas grid can distribute the same amount of hydrogen as natural gas. Grid operators only need to make minor adjustments to make the grid suitable for the transportation of hydrogen. These costs will not be affected by the level of reliability. Concludingly, the upfront investment costs determine the price differences for the level of reliability maintained in the hydrogen grid.

3. *What are the most valued attributes and the most important choices by the public for designing a green hydrogen grid used for heating based on discrete choice modeling?*

This research uses Discrete Choice Modeling (DCM) to answer this question. The design variables analyzed are the amount of cost reduction, the period with demand constraints at which there is a maximum indoor temperature in a particular number of rooms.

Based on the results of the DCM, it became apparent that the maximum indoor temperature mostly influences the choice for an alternative. Also, the cost reduction significantly influences the choice of the system used for heating. Both attributes are valued positively, which means that if the maximum indoor temperature increases, the utility obtained from the heating alternative increases (if the other variables stay the same). When the cost reduction increases or the maximum indoor temperature increases, the utility derived from this alternative increases (ceteris paribus).

After the maximum indoor temperature and the cost reduction, the amount of rooms heated is the most critical factor influencing the choice for a system used for heating. There is a dislike for heating only one room. When considering “three rooms,” it has become apparent that generally, the respondents gain utility when “three rooms” are heated compared to “all rooms.” Respondents could choose between two sustainable hydrogen alternatives with a lower level of reliability and one natural gas system. A possible explanation for the relationship between “three rooms” and “all rooms” heated can be that respondents gain utility from an alternative hydrogen design. The natural gas alternative can always heat all rooms. Therefore, respondents may gain utility when only three rooms are allowed to be heated in a hydrogen system with a specific cost reduction. The utility gained from “three rooms” heated implies that this level is not reducing the level of comfort. However, this attribute level was found to be insignificant, and no conclusions on the population level can be made. Finally, time constraint least influenced the choice for a system used for heating, compared to the other attributes. The utility derived from time is negative; this implies that if the alternative has a more extended period with demand constraints, the utility of the alternative decreases (if the other attributes stay constant).

Heterogeneity in the attributes “cost reduction,” “number of rooms heated,” and “maximum indoor temperature” is measured. Not all households do obtain the same amount of utility from changing these variables. Finally, there is a mean preference for a hydrogen system with a lower level of reliability over the current natural gas system. This preference implies that households are willing to change their demand pattern in a hydrogen design in exchange for money.

4. *What explanatory factors significantly influence the choice of a hydrogen system with a different level of reliability?*

Households with insights into their gas use have a higher Willingness To Pay (WTP) for reliability. An explanation could be that this group is more aware of their gas use and know how to reduce their costs without reducing the level of comfort. Also, the maintained indoor temperature influences the WTP for reliability. Households that maintain a higher indoor temperature have a higher WTP for reliability than households that maintain a lower indoor temperature. Households maintaining a high indoor temperature (above 20°C) seem to like the level of reliability that the natural gas system guarantees. Households that maintain an indoor temperature below 20°C consider the current system as too expensive. Both variables explain part of the heterogeneity in the sensitivity of the households.

Primarily houses that are not well insulated will be connected to the hydrogen infrastructure. The WTP of households living in less insulated houses is essential when determining the level of reliability for the hydrogen system. Based on the WTP estimates, it is clear that, on average, households living in less insulated houses have a significantly higher WTP for reliability than households living in well-insulated houses. However, there is still a gap between the WTP and the cost of the current natural gas system, based on a 95% confidence interval. Concluding, when designing a future proof hydrogen system, it is essential to keep in mind that the houses connected to the hydrogen grid will be less insulated and use more hydrogen to be kept thermally comfortable. However, the cost of reliability already exceeds the WTP for households living in less insulated houses. Therefore, the cost of the hydrogen system must not increase too much.

Households that expect using sustainable heating and have a positive expectation of hydrogen in the built environment are likely to choose a hydrogen system with a lower level of reliability. It seems plausible to assume that this group sees the reduced level of reliability as something inevitable for the transition to sustainable heating.

The expectation of using sustainable heating also influence the WTP for reliability. Households that expect to use sustainable heating have a lower WTP for the reliability of the (hydrogen) system used for heating.

Households expecting to use sustainable heating are willing to disconnect their house from the natural gas grid and use sustainable heating as an alternative. The first neighbourhoods that shift from natural gas to hydrogen are willing to use sustainable heating. Currently, grid operators cannot force households to change their heating connections from natural gas to sustainable fuels. Stedin expects that in the future a certain percentage of supporters for changing the infrastructure used for heating is necessary to change the natural gas infrastructure. For example, the future rule could become that if 90% of the inhabitants of the neighbourhood support the transition from natural gas to hydrogen, the remaining 10% can be forced to change their heating connection. However, the attitude towards hydrogen should be positive to induce change.

The transition phase is expensive, especially if the system has to be very reliable from day one. The results imply that households willing to use sustainable heating prefer to reduce the reliability of the sustainable system to ensure the sustainable system will not become too expensive. Therefore, it may be a solution to make the reliability regulations for the transition phase less strict than in the final phase. Transition regulations can help the development of an affordable, reliable, and sustainable hydrogen grid.

5. *To what extent equals the cost of reliability services in the current natural gas system the Willingness To Pay (WTP) of households?*

The results from this research imply a gap between the average WTP for reliability and the cost of the natural gas system. The cost for reliability services of the natural gas system exceeds the households' WTP for reliability.

Literature expects that a hydrogen system will be more expensive than the current natural gas system, especially in the transition phase. In the beginning, there are no infrastructure or generation facilities. The implementation of expensive hydrogen infrastructures on a local level will significantly increase the cost. The construction of an electrolyser serving demand until -7℃ instead of -12℃ can decrease the cost by 15%. The cost reduction caused by lowering the investment costs can decrease the gap between the WTP and the cost of heating. Cost reductions of 15% ensure that the gap between the WTP and the cost cannot be concluded on a 95% confidence interval, which implies that this research is not able to conclude the gap with 95% certainty.

If the current regulation forces the grid operators and energy companies to implement a hydrogen system that meets the current reliability regulation, the gap between the WTP of households and the cost of heating will further increase.

There is still uncertainty about the exact cost and the deviation of the cost for a hydrogen system. For example, it is unknown whether every affiliate to the natural gas system will pay for the transition cost to a hydrogen system or if only inhabitants of the neighborhood connecting to hydrogen will pay to construct the hydrogen infrastructure. Therefore, this report cannot draw specific conclusions about the WTP for reliability and the cost for reliability in a hydrogen system.

Different explanatory factors influence the WTP for reliability. Households are differently sensitive to cost reductions. This research found that, in general, households that obtain more utility from a reliable system used for heating have a higher WTP for reliability. For example, households obtain a higher utility by maintaining a higher indoor temperature or by using more hydrogen due to the lack of insulation measures.

The final research question is:
"What are the preferences of Dutch households in the design of a reliable and affordable green hydrogen grid in the built environment?"

A hydrogen system has to be reliable in the sense that no interruptions occur in the system. Based on the trade-off from the households' perspective, it becomes apparent that next to a reliable energy system, the affordability of a system is crucial. Affordability should not be a goal in itself, and the system must always guarantee a certain level of reliability.

This research states that, on a 95% confidence interval, there is a gap between the Willingness To Pay (WTP) for reliability and the actual cost of reliability. This means that this research can conclude there is a gap between the WTP and de cost for reliability with 95% certainty. The expectation is that the cost of a hydrogen system will be higher compared to the current natural gas system. Subsequently, the gap between the WTP for reliability and the cost of reliability will increase.

The affordability of a system is essential to households, and the natural gas grid is considered too expensive. Therefore, grid operators should not entirely determine the trade-off between reliability and affordability on the level of reliability. Households are sensitive to cost reductions. Subsequently, grid operators can use flexible demand to make the system less reliant on the supply of hydrogen. Financial consequences can stimulate households to reduce their hydrogen demand during peak hours.

It is crucial to reconsider the reliability regulations to start the transition to a sustainable built environment. The government should reconsider the national reliability regulations. The weather conditions have changed the last decades, and from the households' perspective, the system is too expensive. A possible national reliability regulation can be based upon the temperatures measured in De Bilt. The temperature measured in De Bilt is the yardstick for the Dutch weather and displays the average temperature in The Netherlands. In the last 20 years, no period of 24-hours with temperatures below -7℃ are measured in this area. Based on this thesis, a cost reduction of 15% can be obtained by lowering the regulations from -12°C to -7°C. Grid operators can reduce the gap between the households' WTP for reliability and the cost for reliability if the applicable regulations are eased. Furthermore, grid operators can prevent interruptions by using different flexibility options on the supply and demand side. Therefore, this research sees -7°C as an appropriate temperature for national reliability regulations.

Besides reconsidering the national reliability regulations, regional reliability regulations seem crucial for the first transition stages. The average minimum temperature in The Netherlands is region-specific and significant differences exist between regions. For example, the coastal areas will have higher minimum temperatures. The hydrogen infrastructure will take off on a local level and should depend on the local conditions. Regional regulations can help to make the system affordable as well as reliable for the particular area.

Furthermore, this research identifies that households with a high expectation of using sustainable heating are less concerned with a lower level of reliability in exchange for money. This research expects that this group sees the reduced level of reliability as a precondition to start the transition to hydrogen. This group has a lower WTP for reliability. The first neighbourhoods that shift from natural gas to hydrogen are the ones that are willing to use sustainable heating since, currently, grid operators cannot force households to change their heating connection. Furthermore, Stedin expects that always a certain percentage of inhabitants should be willing to change their heating connection before a sustainable system used for heating can be implemented. A transition not supported by inhabitants is hard to accomplish.

This research identifies the need that the first hydrogen projects must start with different reliability regulations. The transition phase will be expensive, especially if the system must have much supply from day one. Within the coming years, grid operators will extend the hydrogen infrastructure. Stedin, as well as literature, expects that in the longer term, there will be a national hydrogen grid and that hydrogen is imported from abroad. In the end, the national grid will absorb the shortages on a local level. The fact that households with a high expectation of using sustainable heating see the reduced level of reliability as a precondition. This creates support for designing transition regulations, which must not have to be as strict as is desired in the future. Less strict transition regulations can ensure an affordable hydrogen system, while demand can create a more reliable hydrogen system. Frontrunners seem willing to reduce their demand during peak hours, creating flexible demand in the coming years.

Currently, the infrastructure used for heating matches supply and demand in a supply oriented way. The generation capacity should meet the demand for peak hours. Besides solely considering the generation capacity, the hydrogen system can use other options to match the supply and demand. On the supply side, the storage of hydrogen on a local level is a possibility. However, the cost of storage should not exceed the investment cost in the generating capacity. Another possibility to store hydrogen is in trucks. Weather experts can forecast cold periods. Before the cold period, the overcapacity of electrolysers can be used to fill trucks with hydrogen. Hydrogen stored in trucks can be transported to areas with shortages. Energy companies and grid operators can use this capacity to overcome shortages on a local level.

Grid operators can use regulations in demand for hydrogen to match supply and demand during peak hours. This research showed that grid operators could stimulate households to reduce their demand during peak hours. Households are sensitive to cost reductions. Alternatively, grid operators can restrict the demand for hydrogen of large hydrogen consumers. In this way, more hydrogen will be available during the cold periods.

Concludingly, the government should reconsider the national reliability regulations and look into creating regional reliability regulations for the transition phase. The system should not be as over reliable as it is today. For the transition phase, it is crucial to look at conditions on a local level. In the coming years, local conditions should be used to determine the trade-off between reliability and affordability. Also, the hydrogen system does not have to be very reliable from day one. Less strict transition regulations can help to start the hydrogen transition affordably. For the design of the reliability regulations, it is important to include the demand.

Finally, not only generation capacity should be used to match supply and demand. Households can reduce their hydrogen demand during peak hours. Grid operators can incentivize households to reduce their demand, or technical constraints can be added to the system to ensure households do not use not too much hydrogen during peak hours. Moreover, advanced conversion systems to spread the demand can be implemented in houses. Finally, grid operators can restrict large consumers in their hydrogen demand. The hydrogen needs to become more affordable and less reliable from the perspective of the households. Grid operators, energy companies, and the government should guarantee reliability but should consider other possibilities. Together they must use the different options available to design a sustainable, reliable, and affordable hydrogen infrastructure.

11.2 Recommendations

This section will discuss different practical recommendations for Stedin, as well as scientific recommendations for further research.

The previous section concludes that the government should adjust the reliability regulations and consider regional and transition reliability regulations. Stedin is a grid operator, and cannot change regulations. Therefore, Stedin should collaborate with other grid operators and perhaps energy companies in The Netherlands and start lobbying to the government. Stedin should point out the necessity of adjusting these regulations to create a sustainable, reliable, and affordable energy system. They must support their lobby by the other possibilities to match supply and demand. Moreover, they must state that a less costly system has more support from Dutch households even if the reliability as defined today slightly decreases. Households consider the current system as too expensive. A new grid should meet their preferences since they are the users and payers of the system. Stedin must lobby for adjusting the national reliability regulations and for considering transition regulations.

The national reliability regulations should be less strict. The minimum 24-hours temperature of -12°C should be raised when considering the current weather conditions. In the last 20 years, the 24-hours temperature measured in De Bilt has never been -7°C or lower. This temperature can be used as the new national minimum temperature until which grid operators need to deliver. In case the temperature does occur, Stedin has other possibilities to match supply and demand. These possibilities are reducing demand and collaborate on the supply side. Grid operators can use these possibilities to ensure no interruptions in the system occur when the reliability regulation is eased. Grid operators must indicate that there are possibilities to engage the demand to match supply and demand. Using both demand and supply leads to a more affordable system since the generation capacity of electrolysers or local storage facilities can decrease.

For reducing the demand, Stedin should research whether it is technically (and legally) possible to implement constraints in the distribution grid. If the distribution grid is smaller near the connection of the house, the household can never use an unlimited amount of hydrogen. In this way, Stedin can restrict the demand during peak hours, while the households can all obtain an equal amount of hydrogen.

Stedin can also create flexible demand by incentivizing households to reduce less hydrogen during peak hours. Households are sensitive to cost reductions, so Stedin can draw up contracts stating that households get a cost reduction if they reduce their demand during peak hours. Financial compensation and fees can help to establish these contracts. Stedin applies non-discriminatory services to all affiliates. If Stedin uses contracts to define the maximum amount of hydrogen, it is suggested to conduct more research about using contracts. Contracts must not infringe the non-discriminatory services of Stedin. Moreover, it is unknown whether the usage of different contracts creates a stable and future-proof hydrogen grid system. Finally, the hydrogen infrastructure is a common-pool resource. The allocation of the cost and benefits of common-pool resources is more complicated than with other resources. This characterization will make it more challenging to set up contracts about allocating the cost and benefits. Further research is needed on how to allocate the cost and benefits of the hydrogen system.

In the field of stimulating households, a more qualitative study can reveal which variables the households consider to be essential when choosing a hydrogen system. This thesis found much unobserved heterogeneity, which implies that there are more variables that households consider than were included in the stated choice experiment. It is essential to retrieve the essential variables of households when incorporating their preferences. Moreover, a qualitative study could reveal the reasoning behind the preferences this thesis discovered. When discovering the reasoning behind the preferences of households, additional steps can be taken to create a hydrogen design desired by households.

Stedin can also ensure that households implement advanced hydrogen conversion systems to spread the demand over a more extended period. Further research should demonstrate how much the demand can be spread by using these technologies.

This report recommends considering contracts together with technical constraints and advanced conversion systems. When making it technically impossible to use more hydrogen than agreed erases the possibility that no hydrogen is available for other households. Moreover, spreading the demand creates less necessity to change demand.

Besides households, it is essential to consider large energy consumers in the regional areas where Stedin wants to implement hydrogen. Large consumers are, for example, factories. Stedin needs to address these large energy consumers and ask whether they want to start a collaboration. Stedin should investigate whether these large consumers are interested in financial compensations for restricting or completely shutting down their hydrogen connection during shortages. In this way, more capacity remains available for more essential purposes. Restricting or disconnecting large consumers will make more hydrogen capacity available than restricting households since these large consumers use much hydrogen.

Stedin can also address other facilities, such as companies, whether they would consider a collaboration. In this way, Stedin can use the demand to ensure enough hydrogen remains available during shortages. Using large consumers to balance the grid during shortages will make the system less dependent on changing perceptions of households. Combinations of both large consumers and households will establish a more stable hydrogen design. The optimum will be dependent on the available large consumers that want to cooperate and the perception of households. Therefore, the design might differ per neighborhood.

All different forms can create flexibility on the demand side. Especially in the coming years, flexible demand should be used to create reliability in the system. Research is needed to determine how the demand can be included in the regulations, so the grid becomes reliable and affordable.

Stedin is not responsible for ensuring enough supply. However, Stedin will likely become responsible for the balancing of demand and supply. Therefore, Stedin has to monitor the supply. To meet the goal of Stedin (ensure a reliable, affordable, and sustainable energy system), Stedin should collaborate with energy companies to determine ways to match supply and demand. Stedin should note that only constructing large electrolysers is conflicting with their affordability goal, while the usage of trucks during shortages may help to achieve the affordability goal. Grid operators and energy companies together should consider the possibilities to match supply and demand. More research is needed in local areas to determine the best options per region.

Stedin should lobby for creating transition regulations. In the coming years, grid operators and energy companies need to build the hydrogen infrastructure. Based on the perspective of households, it is not necessary to implement a very reliable hydrogen system from day one. This research raises the idea that the group of households that wants to use hydrogen sees a reduction in reliability as a condition to create a hydrogen infrastructure affordably. Therefore, the possibility to create less strict transition regulations should be investigated.

Furthermore, regional reliability regulations can make sure the grid on a regional level meets the regional conditions. Regional regulations ensure that the grid is not unnecessarily expensive and that it meets the regional weather conditions. To determine the wishes of households in the neighborhood, Stedin should do local research for the design of the hydrogen projects. The local research will help to establish regional regulations with the support of the households.

Besides recommendations inside the scope of this research, it is essential to do further research outside the scope. First of all, research should investigate what the influence of large generation capacity is on the electricity system. Green hydrogen is made from sustainable electricity. If the regulations do not change, much electricity is needed to fuel the electrolysers. The indirect effect on the electricity system is unknown.

Furthermore, research is needed into the design of heating systems of other sustainable sources. This thesis investigated a hydrogen system. Similar studies to all-electric or heating grids can reveal the trade-off in these systems from the perspective of households. It is unknown whether similar conclusions can be drawn for heating infrastructures or all-electric grids. For the design of these grids, a similar study will be relevant.

Finally, more research must be conducted about distributing the cost of a hydrogen infrastructure and the current natural gas infrastructure. Examples of further research are: who will pay to implement a new hydrogen system? Will only the households connected to the new infrastructure pay for the new infrastructure? Or will all the affiliates to the gas system pay? Moreover, the current cost of the natural gas system is divided by every affiliate of the natural gas system. If the number of affiliates of the natural gas system will decrease, while the cost of the system remains almost equal, who will pay for the remaining cost of the natural gas infrastructure? This problem also falls back on the fact that the hydrogen and natural gas infrastructure are common-pool resources, which makes the division of the cost and benefits more challenging.

Concludingly, Stedin should start collaborating with other grid operators and perhaps energy companies. They must lobby to make the government ease the national reliability regulations. This research suggests the average temperature of -7℃ to create a sustainable, affordable, and reliable system desired by households. Furthermore, the grid operators should lobby for creating transition regulations that focus on the regional character of the transition and the fact that the first neighbourhoods are frontrunners in the hydrogen system. Stedin should support the lobby by identifying different options to match supply and demand during shortages. They need to collaborate with energy companies and monitor the available hydrogen supply.

Moreover, grid operators should consider the different options to ensure that they can lower demand during shortages. They need to identify large energy consumers and inventory their willingness to reduce their demand during shortages. Also, they should consider ways to incentivize households to reduce their demand and whether it is legally possible to create contracts for end-users. The possibility of using technical constraints and advanced hydrogen conversion systems to reduce demand must be investigated. One should research how to include the demand in the reliability regulations.

Research must determine to what extent the wishes of the households can be taken into account for the design of a future proof hydrogen system. The design must be stable and not much influenced by the changing perceptions of households. Qualitative research can provide insights into ways to incorporate flexible demand and the preferences of households in the hydrogen design. Moreover, qualitative research is necessary to determine what aspects of energy systems the households find essential.

The influence of generating more hydrogen on the capacity of sustainable electricity sources is left out of scope. One can expect that when more hydrogen capacity must be available, more electricity capacity is needed—this leads to an even more expensive infrastructure. More research should reveal the exact influence. Finally, this research focusses on the incorporation of the preferences of households on the design of a hydrogen grid. Further research should indicate whether the same relations can be found in infrastructures running on other heating sources, as electricity and heating grids.

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Appendix A – Expected cost electrolyser 2030

The construction cost of electrolysers are expected to decrease in the coming years. Based on the expectations of TKI (2018) and TKI (2019) a load factor of 50 kWh/kg H_2 can be obtained and the investment costs will decrease till a range of 300 – 400 €/kW. Based on these numbers, the expected construction costs in 2030 can be determined. The calculation of the construction costs is the same as in section 3.3. The capacity needed for an electrolyser serving demand till a minimal 24-hours temperature of -12°C is 2.736 m^3/h, and the capacity for electrolyser serving demand till a minimal 24-hours temperature of -9°C, -7°C and -5°C is respectively 2.502 m^3/h, 2.346 m^3/h and 2.190 m^3/h. The density of hydrogen is 0,0089 kg/m^3 and the load factor is 50 kWh/kg H_2. Multiplying this results in 4,45 kWh/m^3. Multiplying this number with the capacity of the electrolyser generates the capacity in kW. This capacity can thereafter be multiplied by the expected construction costs of €400/kW. There is chosen for the upper bound since it is an expectation and this creates the least beneficiary cost reduction. Moreover, in the end, a higher cost reduction will be more preferred by the citizens than the other way around. These numbers can be seen in Table A.1.

Table A.1 - Capacity and construction cost electrolyser

Minimal 24-hour temperature	**Capacity [kW]**	**Construction cost (€400/kW)**
-12°C	12.175,2 kW	± €4.900.000
-9°C	11.133,9 kW	± €4.500.000
-7°C	10.439,7 kW	± €4.200.000
-5°C	9.745,5 kW	± €3.900.000

From the construction costs, the cost reduction can be calculated by lowering the capacity of the electrolysers. These can be seen in Table A.2.

Table A.2 - Construction cost electrolyser

Minimal 24-hour temperature	**Cost reduction (€400/kW)**
-9°C	8,5%
-7°C	14,3%
-5°C	20%

For simplicity reasons, it is assumed that with the construction of an electrolyser serving demand till an outside minimal temperature of -12°C, the same average energy bill will be achieved, namely €1.035 per year. By multiplying the cost reduction with the average energy bill of €1.035, results in the cost reduction that can be obtained by lowering the electrolyser capacity. In reality, it is expected that the energy bill will increase by the use of green hydrogen compared to natural gas. However, the cost reduction obtained by lowering the capacity will then be even larger. The cost reductions are rounded up after multiplication.

The following cost reductions can be achieved by construction costs of (€400/kW):
-9°C implies a cost reduction of €90 per year;
-7°C implies a cost reduction of €150 per year;
-5°C implies a cost reduction of €210 per year.

These cost reductions fall in the range of cost reduction calculated in the current situation. Therefore, the current situation, with a larger range is considered in the stated preference experiment.

Appendix B – Choice models

Alternative i is chosen by individual n if (Chorus, 2018):
$\sum_m \beta_m * x_{im} + \cup_{n,hydrogen} + \varepsilon_{in} > \sum_m \beta_m * x_{jm} + \cup_{n,hydrogen} + \varepsilon_{jn}, \forall j \neq i$

For simplicity reasons, the n is left out and the following functions can be obtained for the total utility:

$$U_i = V_i + \cup_{hydrogen} + \varepsilon_{in} = \sum_m \beta_m * x_{im} + \cup_{hydrogen} + \varepsilon_i$$

And the decision rule:

$\sum_m \beta_m * x_{im} + \cup_{hydrogen} + \varepsilon_i > \sum_m \beta_m * x_{jm} + \cup_{hydrogen} + \varepsilon_j, \forall j \neq i$

Appendix C – Feedback pilot study

Before the complete survey was conducted, a pilot was performed. This Appendix explains the feedback from the pilot study, which was changed in the final version of the survey that is conducted.

- The different attribute levels of the stated choice experiment for the indoor temperature and the number of rooms heated were separated by a and b. The respondents found this indication unclear since they thought they had to choose between the two attributes levels. Therefore, in the final survey, there was chosen to use "&" between the attribute levels.

- The respondents of the pilot survey indicated that they considered 16℃ too cold and that they would not choose the alternative with an indoor temperature of 16℃. In the final survey a minimal temperature of 17℃ is used.

- The second part of the survey was considered hard to answer. The respondents had the idea that they needed to answer the questions correctly instead of answer it based on their opinion. Therefore, in the final survey, this part was conducted based on the Likert Scale and just asked about the opinion of the respondents. A statement was formulated and the respondent is asked to fill in to what extent he/she agrees with this statement.

- Some of the respondents filled the survey in on their mobile phone and it is expected that this will also be done by the final survey. Therefore, by the introduction of the stated choice experiment, a sentence was added that the explanation of the choice set was added beneath the example.

- In the final page of the survey, a final sentence was added that the respondent needs to click on the arrow to the right to hand in the survey. It was noticed that not all respondents handed in the survey since they thought the final page was already the end of the survey.

Appendix D – Ngene design

The experimental design is obtained by using the software Ngene. Since an efficient design needs to be created, the priors should be estimated. Walker, et al. (2018) stated that an optimal design can be created by dividing plus or minus one by the range of the attributes. The dummy coded attributes should be coded with -0.5|-0.25. This includes only the attributes of the hydrogen design.
For this research, the following mean Bayesian priors are estimated:
Cost reduction: 1/130 = 0.008
Time: -1/26 = -0.04
Temperature: 1/4 = 0.25
Room: -0.5|-0.25

The following syntax was used in Ngene to obtain the experimental design:

```
Design
;alts = alt1*, alt2*
;rows = 12
;eff = (mnl, d, mean)
;block = 2
;model:
U(alt1) = b1[(n,0.008,0.004)] * cost[80,145,210] + b2[(n,-0.04,0.02)] * time[3,10,29] +
b3[(n,0.25,0.125)] * temp[17,19,21] + b4.dummy[(n,-0.5,0.25)|(n,-0.25,0.125)] * room[0,1,2]/
U(alt2) = b1 * cost + b2 * time + b3 * temp+ b4.dummy * room
$
```

The attribute "room" is dummy coded, with a reference value all rooms, since this is the case in the current situation. The other attribute levels are continuous and no coding has to be applied. Table D.1 displays all the attributes, together with the attribute levels and the coding of the dummy variable.

Table D.1 - Coding attributes and attribute levels

Attribute	**Attribute level**
Cost reduction (cost)	- €80 per year - €145 per year - €210 per year
Time per year in which energy use should be decreased (time)	- 3 hours per year - 10 hours per year - 29 hours per year
Indoor temperature (temp)	- 17℃ - 19℃ - 21℃
Amount of rooms heated (room)	- 1 room (0) - 3 rooms (1) - All rooms (2 = reference value)

The choice set construction for the experimental design is shown in Table D.2. To obtain the eventual choice set, the coding for the dummy variable "room" should be replaced by the corresponding attribute levels defined in Table D.1.

Table D.2 - Choice sets

Choice	Cost1	Time1	Temp1	Room1	Cost2	Time2	Temp2	Room2	Block
1	210	10	17	1	80	10	21	2	2
2	80	3	19	0	210	29	19	2	1
3	145	10	21	2	145	3	17	0	2
4	80	3	19	2	210	29	19	0	2
5	145	29	21	1	145	3	17	2	1
6	145	3	19	0	80	29	19	1	1
7	145	3	17	1	145	29	21	2	2
8	80	29	21	0	210	10	17	1	2
9	80	10	17	2	210	10	21	0	1
10	210	29	21	1	145	3	17	0	1
11	210	29	17	2	80	3	21	1	1
12	210	10	19	0	80	10	19	1	2

After the construction of the experiment design by Ngene it is important to look at the MNL probability to check for utility balance. A choice probability closer to one implies only limited information about the trade-off. As a rule of thumb, the MNL probability should always be lower than or equal to 0.90 to check for the utility balance (Molin, 2018). From Table D.3 it can be concluded that the largest probability is 0.823456. Therefore, the utility of the experiment design is balanced.

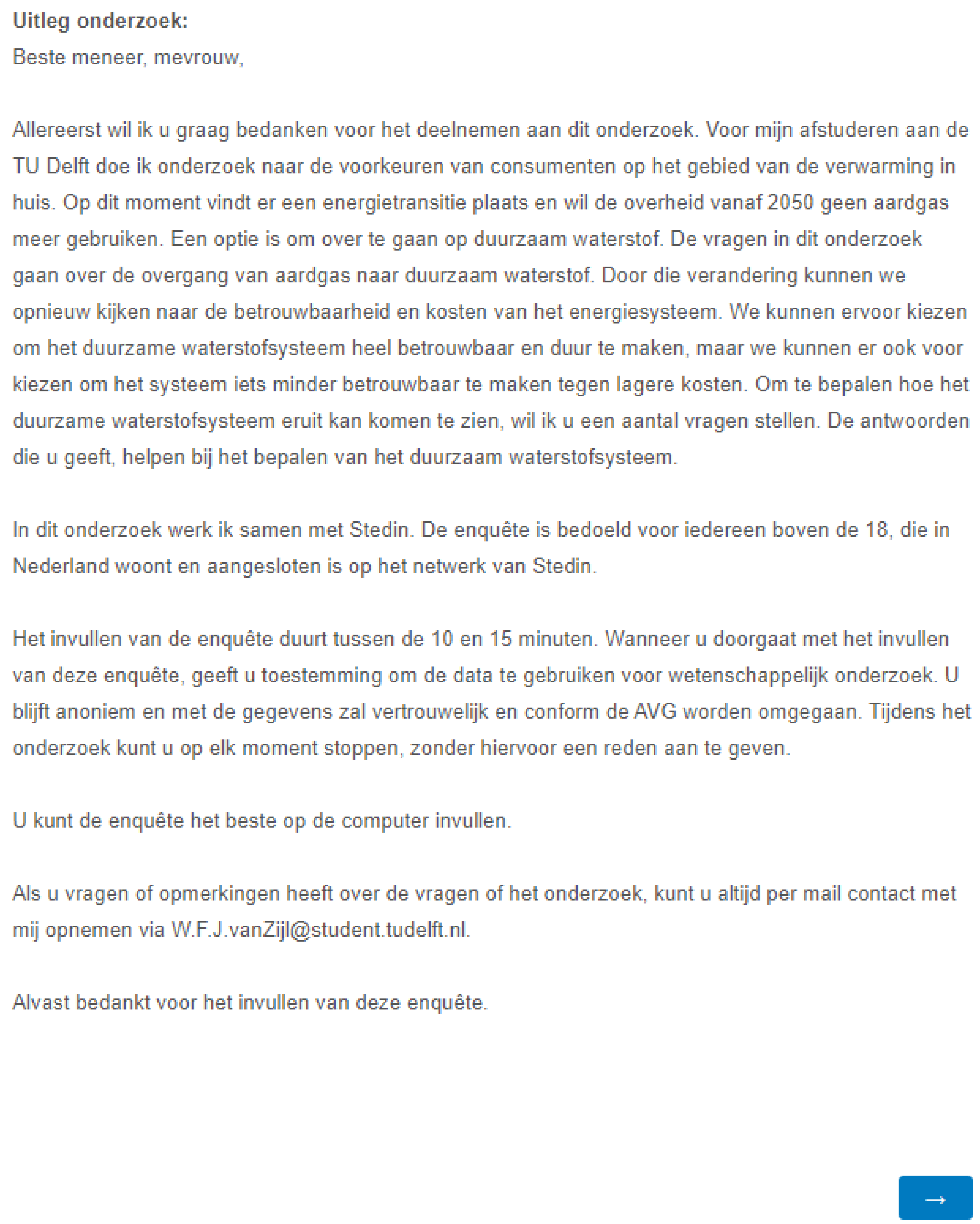
MNL probability is shown below in Table D.3.

Table D.3 - MNL probability

Choice situation	Alternative 1	Alternative 2
1	0.447692	0.552308
2	0.377541	0.622459
3	0.772064	0.227936
4	0.622459	0.377541
5	0.428004	0.571996
6	0.787513	0.212487
7	0.447692	0.552308
8	0.259225	0.740775
9	0.176535	0.823465
10	0.674805	0.325195
11	0.320821	0.679179
12	0.687831	0.312169

Appendix E – Online survey

Beneath the survey is displayed in the online format Quatrics. First, the complete survey of version A is displayed, after which the discrete choice experiment of version B is shown.



Uitleg onderzoek:
Beste meneer, mevrouw,

Allereerst wil ik u graag bedanken voor het deelnemen aan dit onderzoek. Voor mijn afstuderen aan de TU Delft doe ik onderzoek naar de voorkeuren van consumenten op het gebied van de verwarming in huis. Op dit moment vindt er een energietransitie plaats en wil de overheid vanaf 2050 geen aardgas meer gebruiken. Een optie is om over te gaan op duurzaam waterstof. De vragen in dit onderzoek gaan over de overgang van aardgas naar duurzaam waterstof. Door die verandering kunnen we opnieuw kijken naar de betrouwbaarheid en kosten van het energiesysteem. We kunnen ervoor kiezen om het duurzame waterstofsysteem heel betrouwbaar en duur te maken, maar we kunnen er ook voor kiezen om het systeem iets minder betrouwbaar te maken tegen lagere kosten. Om te bepalen hoe het duurzame waterstofsysteem eruit kan komen te zien, wil ik u een aantal vragen stellen. De antwoorden die u geeft, helpen bij het bepalen van het duurzaam waterstofsysteem.

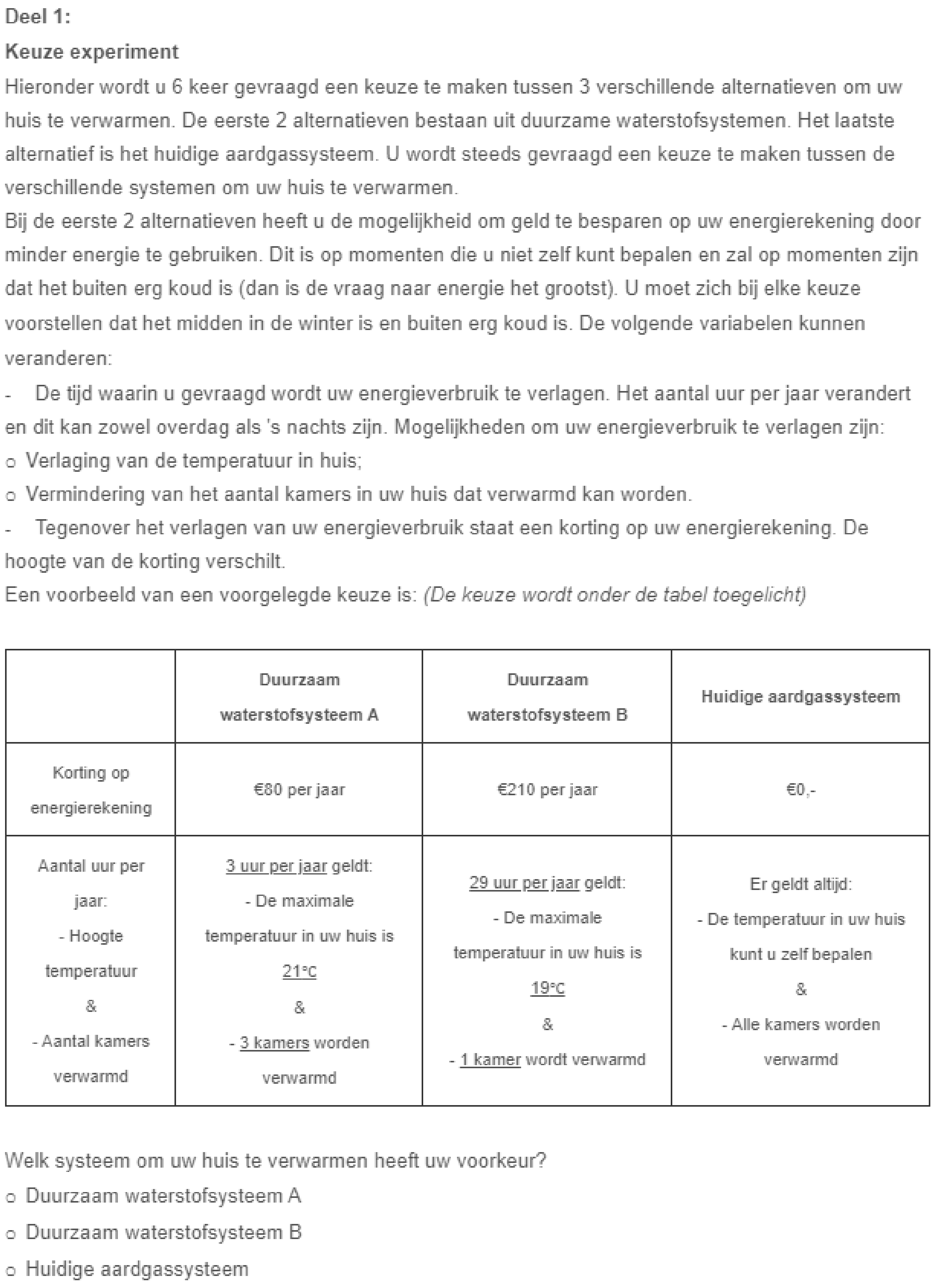
In dit onderzoek werk ik samen met Stedin. De enquête is bedoeld voor iedereen boven de 18, die in Nederland woont en aangesloten is op het netwerk van Stedin.

Het invullen van de enquête duurt tussen de 10 en 15 minuten. Wanneer u doorgaat met het invullen van deze enquête, geeft u toestemming om de data te gebruiken voor wetenschappelijk onderzoek. U blijft anoniem en met de gegevens zal vertrouwelijk en conform de AVG worden omgegaan. Tijdens het onderzoek kunt u op elk moment stoppen, zonder hiervoor een reden aan te geven.

U kunt de enquête het beste op de computer invullen.

Als u vragen of opmerkingen heeft over de vragen of het onderzoek, kunt u altijd per mail contact met mij opnemen via W.F.J.vanZijl@student.tudelft.nl.

Alvast bedankt voor het invullen van deze enquête.



Deel 1:

Keuze experiment

Hieronder wordt u 6 keer gevraagd een keuze te maken tussen 3 verschillende alternatieven om uw huis te verwarmen. De eerste 2 alternatieven bestaan uit duurzame waterstofsystemen. Het laatste alternatief is het huidige aardgassysteem. U wordt steeds gevraagd een keuze te maken tussen de verschillende systemen om uw huis te verwarmen.

Bij de eerste 2 alternatieven heeft u de mogelijkheid om geld te besparen op uw energierekening door minder energie te gebruiken. Dit is op momenten die u niet zelf kunt bepalen en zal op momenten zijn dat het buiten erg koud is (dan is de vraag naar energie het grootst). U moet zich bij elke keuze voorstellen dat het midden in de winter is en buiten erg koud is. De volgende variabelen kunnen veranderen:

- De tijd waarin u gevraagd wordt uw energieverbruik te verlagen. Het aantal uur per jaar verandert en dit kan zowel overdag als 's nachts zijn. Mogelijkheden om uw energieverbruik te verlagen zijn:

○ Verlaging van de temperatuur in huis;

○ Vermindering van het aantal kamers in uw huis dat verwarmd kan worden.

- Tegenover het verlagen van uw energieverbruik staat een korting op uw energierekening. De hoogte van de korting verschilt.

Een voorbeeld van een voorgelegde keuze is: *(De keuze wordt onder de tabel toegelicht)*

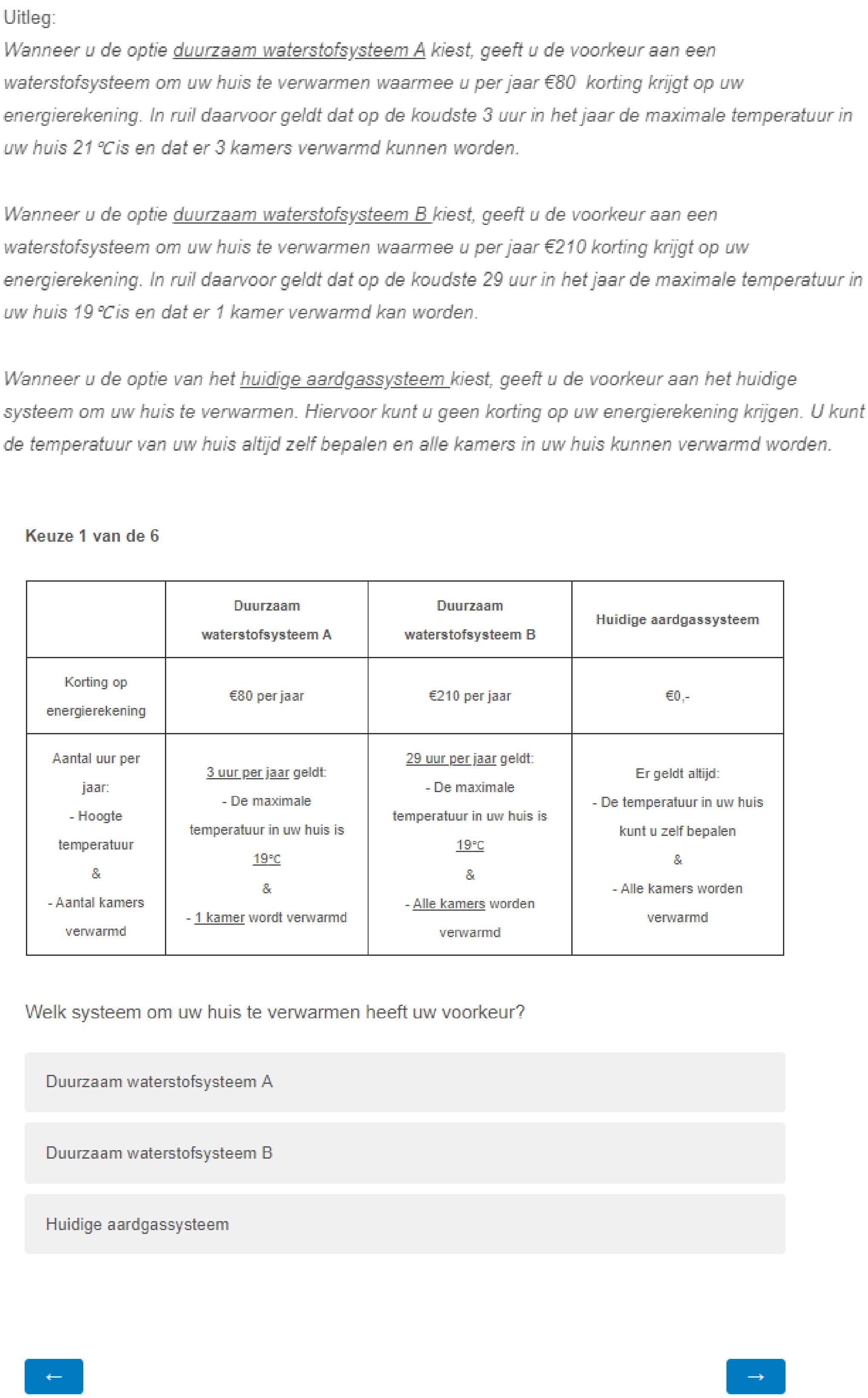
	Duurzaam waterstofsysteem A	**Duurzaam waterstofsysteem B**	**Huidige aardgassysteem**
Korting op energierekening	€80 per jaar	€210 per jaar	€0,-
Aantal uur per jaar: - Hoogte temperatuur & - Aantal kamers verwarmd	3 uur per jaar geldt: - De maximale temperatuur in uw huis is 21°C & - 3 kamers worden verwarmd	29 uur per jaar geldt: - De maximale temperatuur in uw huis is 19°C & - 1 kamer wordt verwarmd	Er geldt altijd: - De temperatuur in uw huis kunt u zelf bepalen & - Alle kamers worden verwarmd

Welk systeem om uw huis te verwarmen heeft uw voorkeur?

○ Duurzaam waterstofsysteem A

○ Duurzaam waterstofsysteem B

○ Huidige aardgassysteem



Uitleg:

Wanneer u de optie duurzaam waterstofsysteem A kiest, geeft u de voorkeur aan een waterstofsysteem om uw huis te verwarmen waarmee u per jaar €80 korting krijgt op uw energierekening. In ruil daarvoor geldt dat op de koudste 3 uur in het jaar de maximale temperatuur in uw huis 21 °Cis en dat er 3 kamers verwarmd kunnen worden.

Wanneer u de optie duurzaam waterstofsysteem B kiest, geeft u de voorkeur aan een waterstofsysteem om uw huis te verwarmen waarmee u per jaar €210 korting krijgt op uw energierekening. In ruil daarvoor geldt dat op de koudste 29 uur in het jaar de maximale temperatuur in uw huis 19 °Cis en dat er 1 kamer verwarmd kan worden.

Wanneer u de optie van het huidige aardgassysteem kiest, geeft u de voorkeur aan het huidige systeem om uw huis te verwarmen. Hiervoor kunt u geen korting op uw energierekening krijgen. U kunt de temperatuur van uw huis altijd zelf bepalen en alle kamers in uw huis kunnen verwarmd worden.

Keuze 1 van de 6

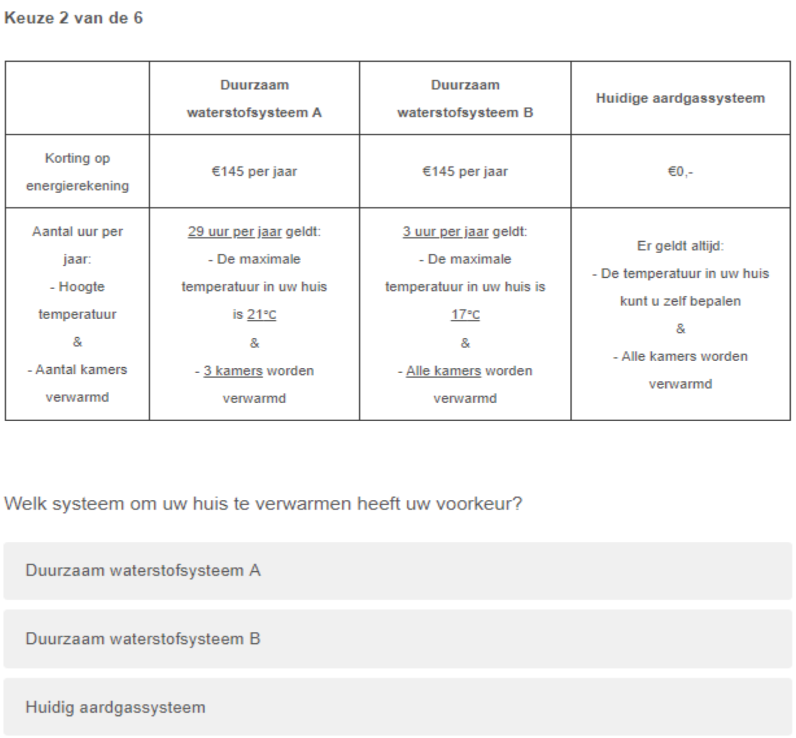
	Duurzaam waterstofsysteem A	**Duurzaam waterstofsysteem B**	**Huidige aardgassysteem**
Korting op energierekening	€80 per jaar	€210 per jaar	€0,-
Aantal uur per jaar: - Hoogte temperatuur & - Aantal kamers verwarmd	3 uur per jaar geldt: - De maximale temperatuur in uw huis is 19°C & - 1 kamer wordt verwarmd	29 uur per jaar geldt: - De maximale temperatuur in uw huis is 19°C & - Alle kamers worden verwarmd	Er geldt altijd: - De temperatuur in uw huis kunt u zelf bepalen & - Alle kamers worden verwarmd

Welk systeem om uw huis te verwarmen heeft uw voorkeur?

Duurzaam waterstofsysteem A

Duurzaam waterstofsysteem B

Huidige aardgassysteem



Keuze 2 van de 6

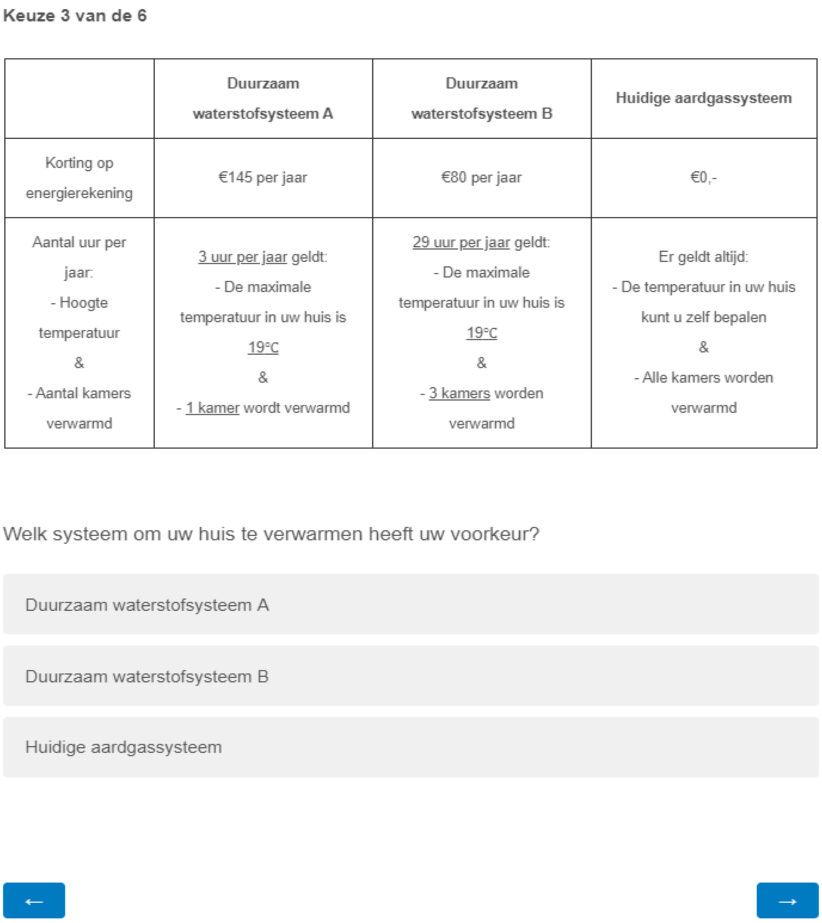
	Duurzaam waterstofsysteem A	Duurzaam waterstofsysteem B	Huidige aardgassysteem
Korting op energierekening	€145 per jaar	€145 per jaar	€0,-
Aantal uur per jaar: - Hoogte temperatuur & - Aantal kamers verwarmd	29 uur per jaar geldt: - De maximale temperatuur in uw huis is 21°C & - 3 kamers worden verwarmd	3 uur per jaar geldt: - De maximale temperatuur in uw huis is 17°C & - Alle kamers worden verwarmd	Er geldt altijd: - De temperatuur in uw huis kunt u zelf bepalen & - Alle kamers worden verwarmd

Welk systeem om uw huis te verwarmen heeft uw voorkeur?

Duurzaam waterstofsysteem A

Duurzaam waterstofsysteem B

Huidig aardgassysteem



Keuze 3 van de 6

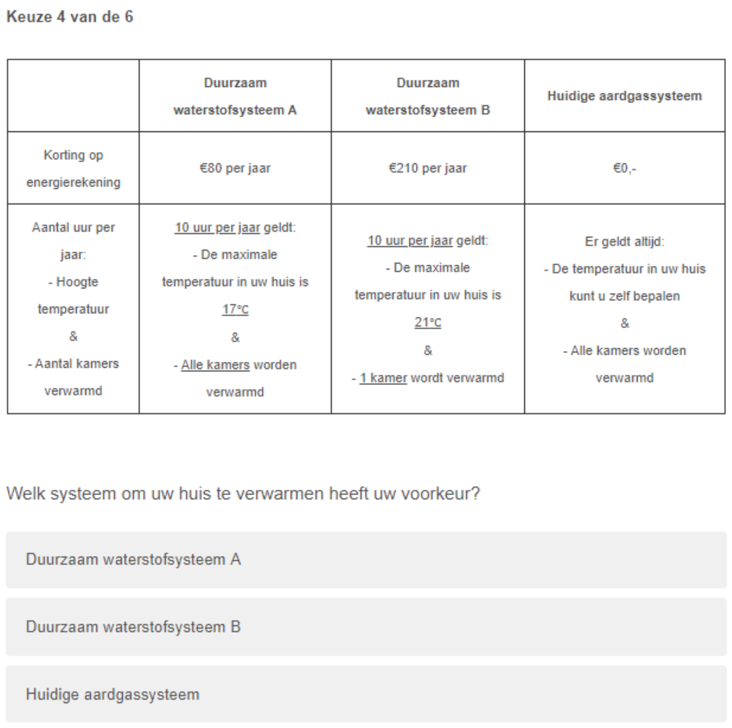
	Duurzaam waterstofsysteem A	Duurzaam waterstofsysteem B	Huidige aardgassysteem
Korting op energierekening	€145 per jaar	€80 per jaar	€0,-
Aantal uur per jaar: - Hoogte temperatuur & - Aantal kamers verwarmd	3 uur per jaar geldt: - De maximale temperatuur in uw huis is 19°C & - 1 kamer wordt verwarmd	29 uur per jaar geldt: - De maximale temperatuur in uw huis is 19°C & - 3 kamers worden verwarmd	Er geldt altijd: - De temperatuur in uw huis kunt u zelf bepalen & - Alle kamers worden verwarmd

Welk systeem om uw huis te verwarmen heeft uw voorkeur?

Duurzaam waterstofsysteem A

Duurzaam waterstofsysteem B

Huidige aardgassysteem



Keuze 4 van de 6

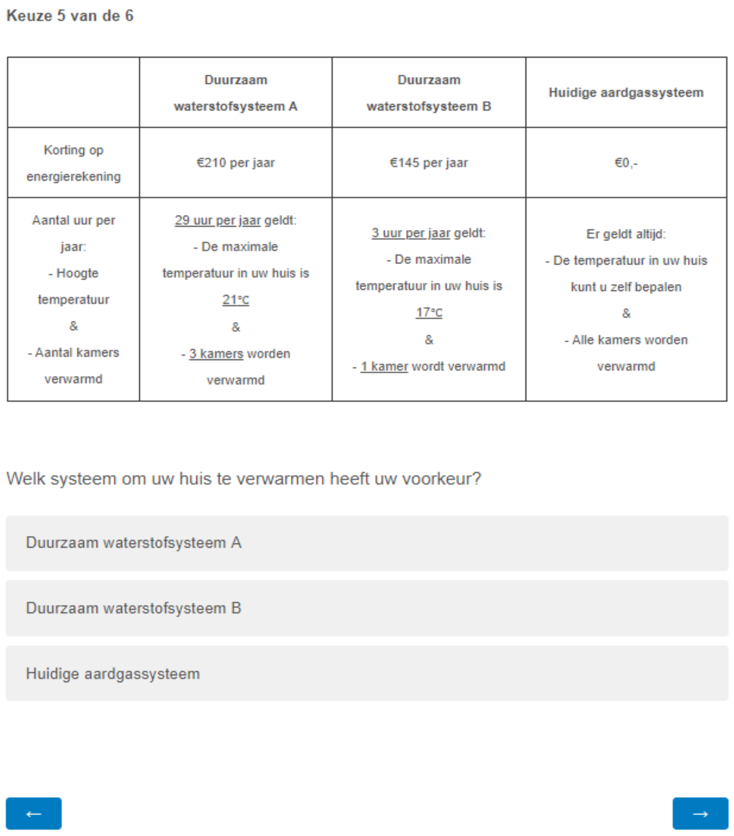
	Duurzaam waterstofsysteem A	Duurzaam waterstofsysteem B	Huidige aardgassysteem
Korting op energierekening	€80 per jaar	€210 per jaar	€0,-
Aantal uur per jaar: - Hoogte temperatuur & - Aantal kamers verwarmd	10 uur per jaar geldt: - De maximale temperatuur in uw huis is 17°C & - Alle kamers worden verwarmd	10 uur per jaar geldt: - De maximale temperatuur in uw huis is 21°C & - 1 kamer wordt verwarmd	Er geldt altijd: - De temperatuur in uw huis kunt u zelf bepalen & - Alle kamers worden verwarmd

Welk systeem om uw huis te verwarmen heeft uw voorkeur?

Duurzaam waterstofsysteem A

Duurzaam waterstofsysteem B

Huidige aardgassysteem



Keuze 5 van de 6

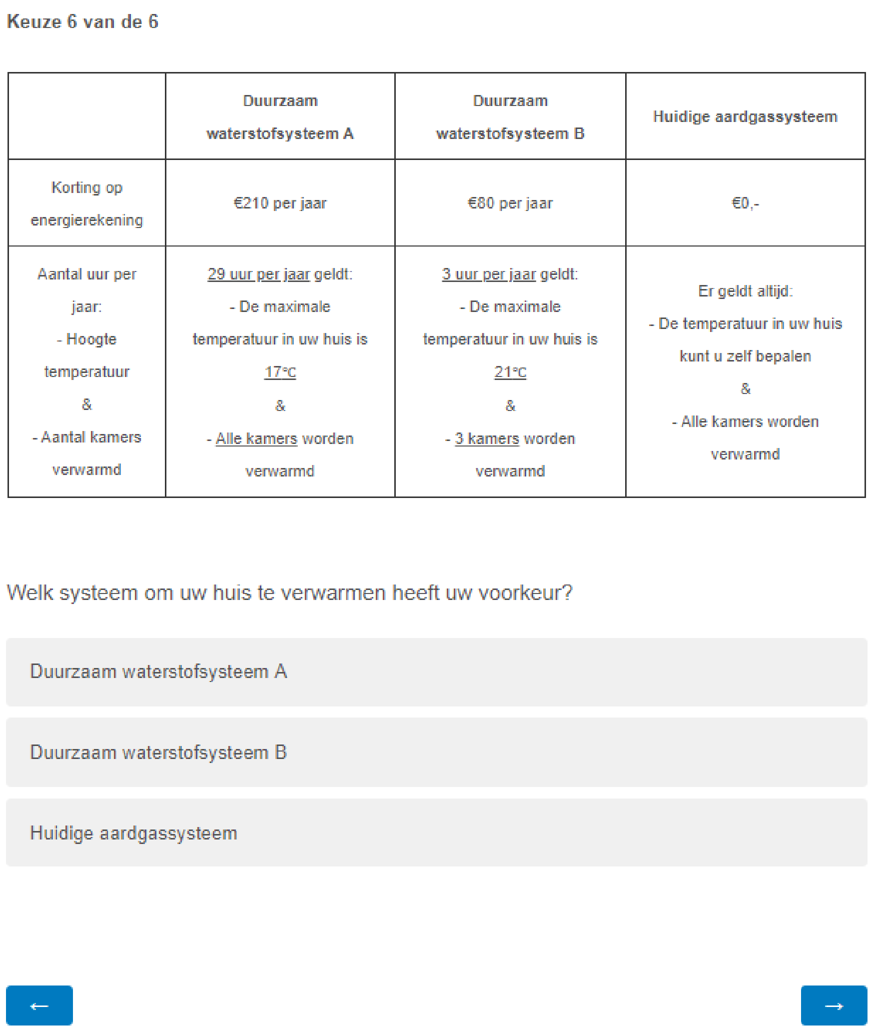
	Duurzaam waterstofsysteem A	Duurzaam waterstofsysteem B	Huidige aardgassysteem
Korting op energierekening	€210 per jaar	€145 per jaar	€0,-
Aantal uur per jaar: - Hoogte temperatuur & - Aantal kamers verwarmd	29 uur per jaar geldt: - De maximale temperatuur in uw huis is 21°C & - 3 kamers worden verwarmd	3 uur per jaar geldt: - De maximale temperatuur in uw huis is 17°C & - 1 kamer wordt verwarmd	Er geldt altijd: - De temperatuur in uw huis kunt u zelf bepalen & - Alle kamers worden verwarmd

Welk systeem om uw huis te verwarmen heeft uw voorkeur?

Duurzaam waterstofsysteem A

Duurzaam waterstofsysteem B

Huidige aardgassysteem



Keuze 6 van de 6

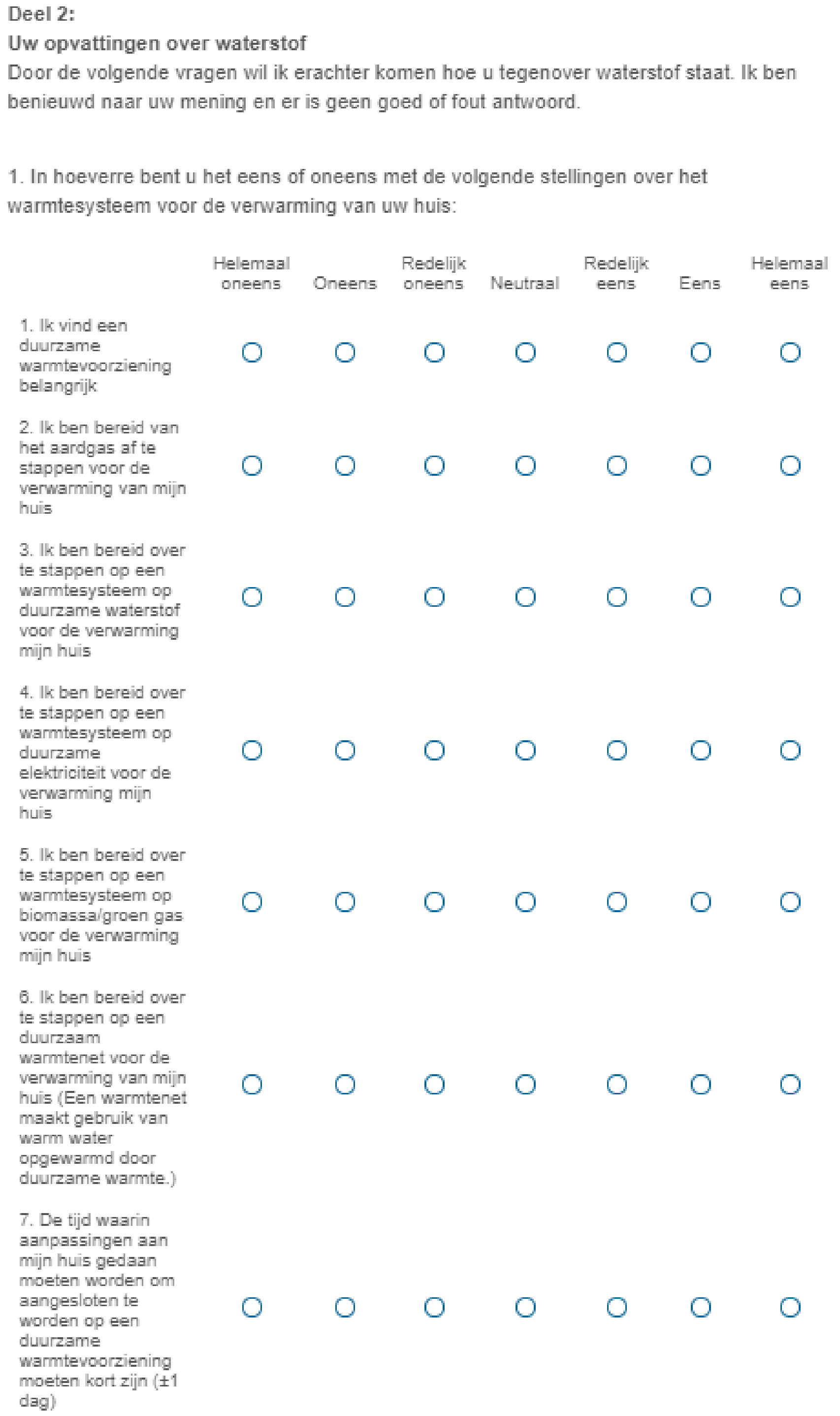
	Duurzaam waterstofsysteem A	**Duurzaam waterstofsysteem B**	**Huidige aardgassysteem**
Korting op energierekening	€210 per jaar	€80 per jaar	€0,-
Aantal uur per jaar: - Hoogte temperatuur & - Aantal kamers verwarmd	29 uur per jaar geldt: - De maximale temperatuur in uw huis is 17°C & - Alle kamers worden verwarmd	3 uur per jaar geldt: - De maximale temperatuur in uw huis is 21°C & - 3 kamers worden verwarmd	Er geldt altijd: - De temperatuur in uw huis kunt u zelf bepalen & - Alle kamers worden verwarmd

Welk systeem om uw huis te verwarmen heeft uw voorkeur?

Duurzaam waterstofsysteem A

Duurzaam waterstofsysteem B

Huidige aardgassysteem



Deel 2:

Uw opvattingen over waterstof

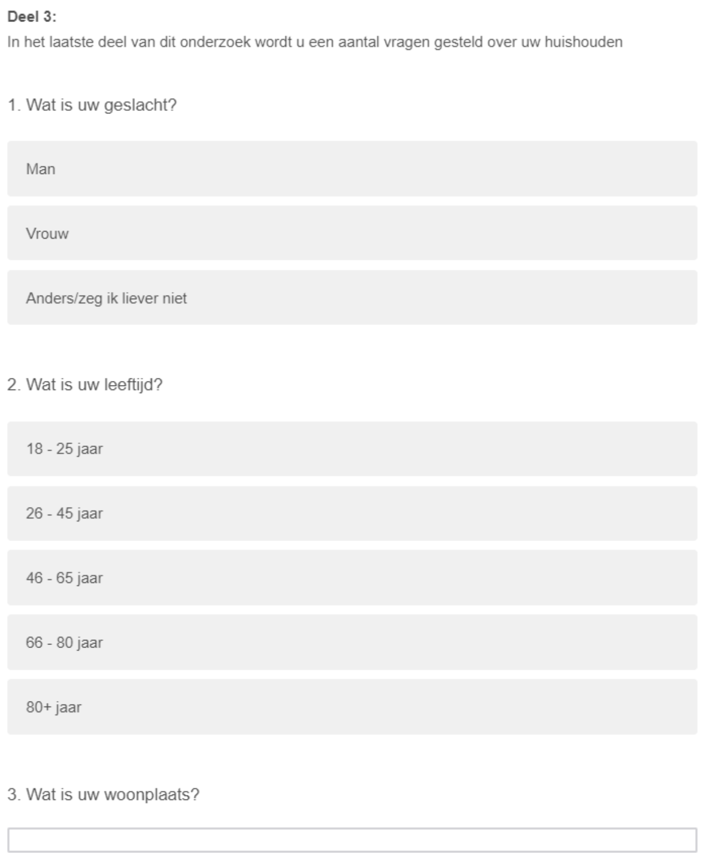
Door de volgende vragen wil ik erachter komen hoe u tegenover waterstof staat. Ik ben benieuwd naar uw mening en er is geen goed of fout antwoord.

1. In hoeverre bent u het eens of oneens met de volgende stellingen over het warmtesysteem voor de verwarming van uw huis:

	Helemaal oneens	Oneens	Redelijk oneens	Neutraal	Redelijk eens	Eens	Helemaal eens
1. Ik vind een duurzame warmtevoorziening belangrijk	○	○	○	○	○	○	○
2. Ik ben bereid van het aardgas af te stappen voor de verwarming van mijn huis	○	○	○	○	○	○	○
3. Ik ben bereid over te stappen op een warmtesysteem op duurzame waterstof voor de verwarming mijn huis	○	○	○	○	○	○	○
4. Ik ben bereid over te stappen op een warmtesysteem op duurzame elektriciteit voor de verwarming mijn huis	○	○	○	○	○	○	○
5. Ik ben bereid over te stappen op een warmtesysteem op biomassa/groen gas voor de verwarming mijn huis	○	○	○	○	○	○	○
6. Ik ben bereid over te stappen op een duurzaam warmtenet voor de verwarming van mijn huis (Een warmtenet maakt gebruik van warm water opgewarmd door duurzame warmte.)	○	○	○	○	○	○	○
7. De tijd waarin aanpassingen aan mijn huis gedaan moeten worden om aangesloten te worden op een duurzame warmtevoorziening moeten kort zijn (±1 dag)	○	○	○	○	○	○	○

2. In hoeverre bent u het eens of oneens met de volgende stellingen over het gebruik van duurzame waterstof voor de verwarming van uw huis

	Helemaal oneens	Oneens	Redelijk oneens	Neutraal	Redelijk eens	Eens	Helemaal eens
1. Het gebruik van duurzame waterstof voor de verwarming van mijn huis is veilig	○	○	○	○	○	○	○
2. Het gebruik van duurzame waterstof voor de verwarming van mijn huis is duur	○	○	○	○	○	○	○
3. Het gebruik van duurzame waterstof voor de verwarming van mijn huis is betrouwbaar	○	○	○	○	○	○	○
4. Het gebruik van duurzame waterstof voor de verwarming in de gebouwde omgeving geeft 100% CO2 verlaging	○	○	○	○	○	○	○



Deel 3:

In het laatste deel van dit onderzoek wordt u een aantal vragen gesteld over uw huishouden

1. Wat is uw geslacht?

Man

Vrouw

Anders/zeg ik liever niet

2. Wat is uw leeftijd?

18 - 25 jaar

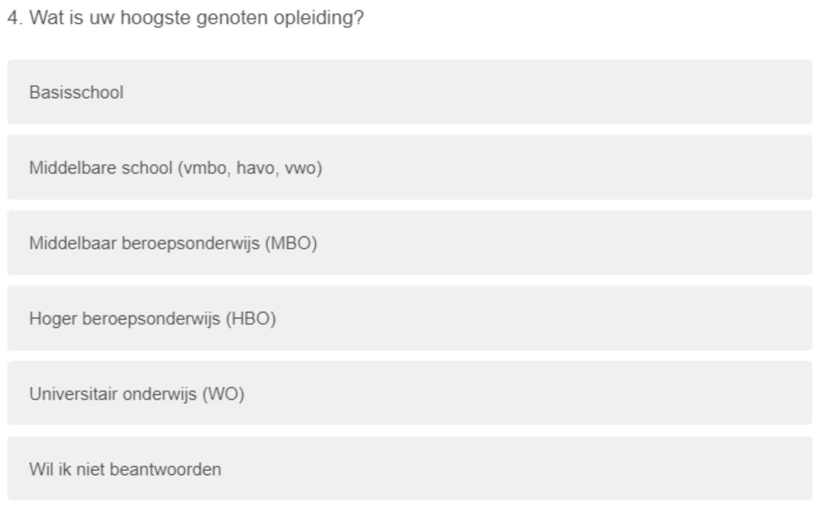
26 - 45 jaar

46 - 65 jaar

66 - 80 jaar

80+ jaar

3. Wat is uw woonplaats?



4. Wat is uw hoogste genoten opleiding?

Basisschool

Middelbare school (vmbo, havo, vwo)

Middelbaar beroepsonderwijs (MBO)

Hoger beroepsonderwijs (HBO)

Universitair onderwijs (WO)

Wil ik niet beantwoorden

5. Wat is het bruto jaarinkomen van uw huishouden? (Dit is uw jaarinkomen plus dat van uw partner wanneer u samenwoont. Het eventuele inkomen van thuiswonende kinderen telt niet mee).

Minder dan €10.000 per jaar

€10.000 - €20.000 per jaar

€20.000 - €30.000 per jaar

€30.000 - €40.000 per jaar

€40.000 - €50.000 per jaar

€50.000 - €60.000 per jaar

€60.000 - €70.000 per jaar

€70.000 - €80.000 per jaar

€80.000 - €90.000 per jaar

€90.000 - €100.000 per jaar

Meer dan €100.000 per jaar

Wil ik niet beantwoorden

6. Wat is het bouwjaar van uw huis?

7. Welk van de onderstaande isolatie maatregelen bevat uw huis? (U kunt meerdere antwoorden kiezen)

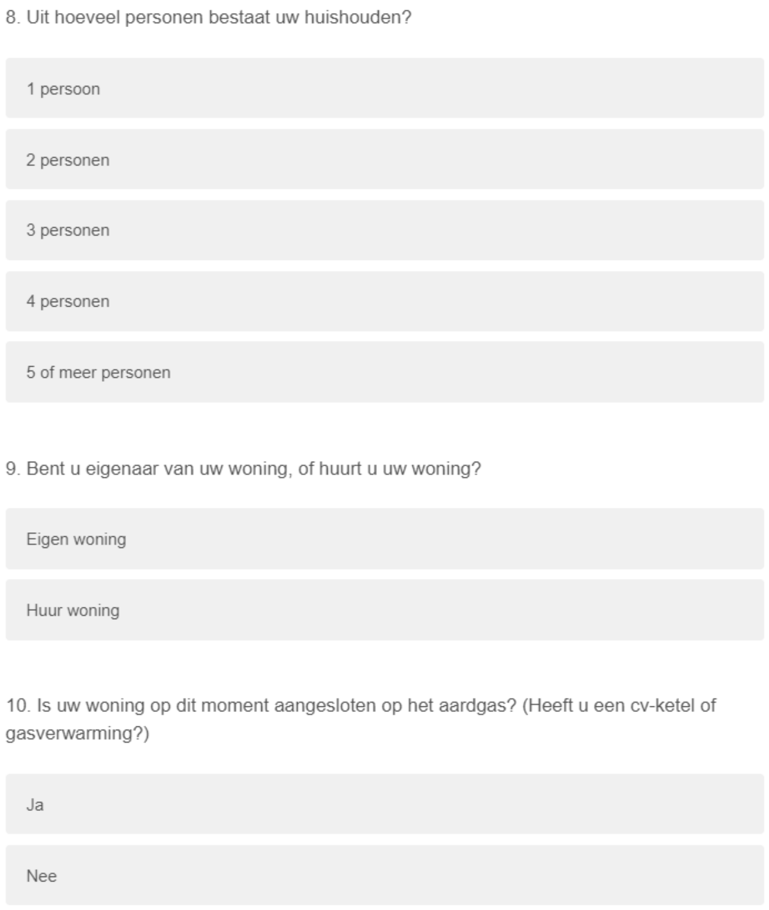
Dubbel glas

Vloerisolatie

Dakisolatie

Gevelisolatie

Spouwmuur isolatie



8. Uit hoeveel personen bestaat uw huishouden?

1 persoon

2 personen

3 personen

4 personen

5 of meer personen

9. Bent u eigenaar van uw woning, of huurt u uw woning?

Eigen woning

Huur woning

10. Is uw woning op dit moment aangesloten op het aardgas? (Heeft u een cv-ketel of gasverwarming?)

Ja

Nee

11. Hoe vaak bent u thuis? (Let op deze vraag gaat over de situatie voor COVID-19)

Meestal

Slechts in de ochtend, avond en nacht en gedurende het weekend

Slechts in het weekend

Slechts in de ochtend, avond en nacht

Nooit

Anders, namelijk:

12. Wat is de gemiddelde temperatuur van uw woning overdag wanneer u thuis bent?

Kouder dan 16°C

16-17°C

17-18°C

18-19°C

19-20°C

20-21°C

21-22°C

22-23°C

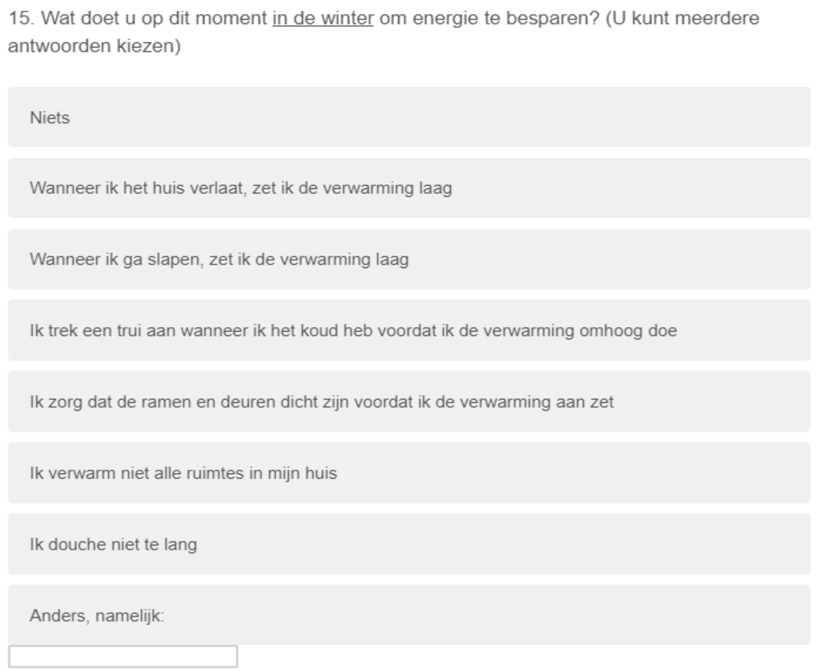
Warmer dan 23°C

13. Wat is de gemiddelde temperatuur van uw woning in de nacht wanneer u thuis bent?

- Kouder dan 16°C
- 16-17°C
- 17-18°C
- 18-19°C
- 19-20°C
- 20-21°C
- 21-22°C
- 22-23°C
- Warmer dan 23°C

14. Heeft u inzage in de kosten van uw gasverbruik?

- Ja
- Nee



15. Wat doet u op dit moment in de winter om energie te besparen? (U kunt meerdere antwoorden kiezen)

- Niets
- Wanneer ik het huis verlaat, zet ik de verwarming laag
- Wanneer ik ga slapen, zet ik de verwarming laag
- Ik trek een trui aan wanneer ik het koud heb voordat ik de verwarming omhoog doe
- Ik zorg dat de ramen en deuren dicht zijn voordat ik de verwarming aan zet
- Ik verwarm niet alle ruimtes in mijn huis
- Ik douche niet te lang
- Anders, namelijk:

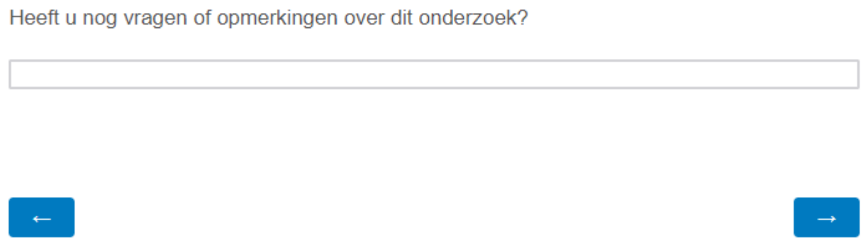
16. Bent u bereid om 's nachts te douchen (tussen 00:00 - 07:00 uur), wanneer dit een aanzienlijke verlaging op uw energierekening geeft?

Ja, dit doe ik al

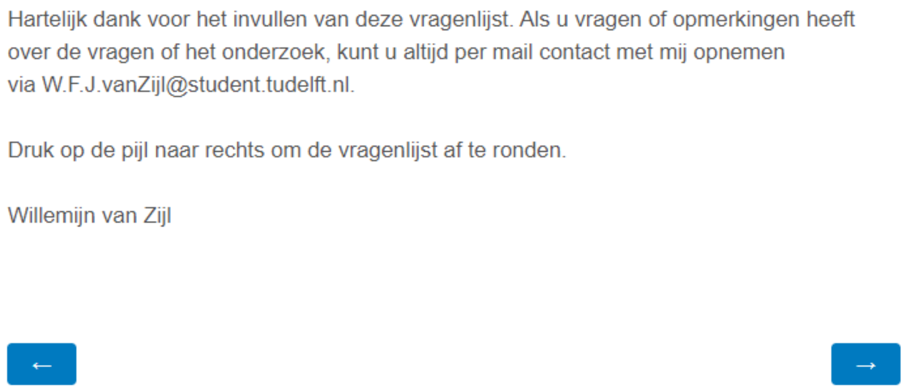
Ja, maar alleen als het me uit komt

Ja, maar niet in de weekenden

Nee



Heeft u nog vragen of opmerkingen over dit onderzoek?



Hartelijk dank voor het invullen van deze vragenlijst. Als u vragen of opmerkingen heeft over de vragen of het onderzoek, kunt u altijd per mail contact met mij opnemen via W.F.J.vanZijl@student.tudelft.nl.

Druk op de pijl naar rechts om de vragenlijst af te ronden.

Willemijn van Zijl

Stated choice experiment of the second version.

Keuze 1 van de 6

	Duurzaam waterstofsysteem A	**Duurzaam waterstofsysteem B**	**Huidige aardgassysteem**
Korting op energierekening	€210 per jaar	€80 per jaar	€0,-
Aantal uur per jaar: - Hoogte temperatuur & - Aantal kamers verwarmd	10 uur per jaar geldt: - De maximale temperatuur in uw huis is 17°C & - 3 kamers worden verwarmd	10 uur per jaar geldt: - De maximale temperatuur in uw huis is 21°C & - Alle kamers worden verwarmd	Er geldt altijd: - De temperatuur in uw huis kunt u zelf bepalen & - Alle kamers worden verwarmd

Welk systeem om uw huis te verwarmen heeft uw voorkeur?

Duurzaam waterstofsysteem A

Duurzaam waterstofsysteem B

Huidige aardgassysteem

Keuze 2 van de 6

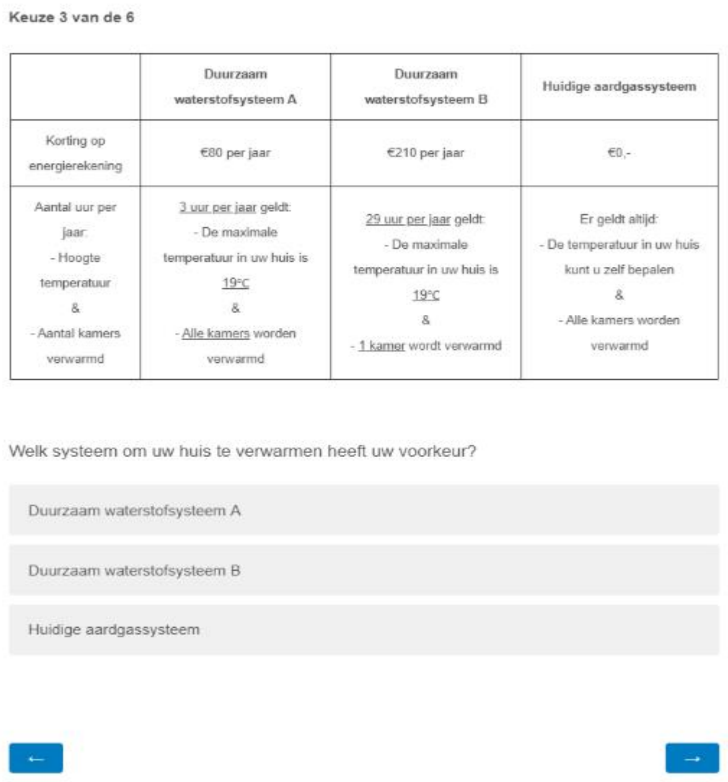
	Duurzaam waterstofsysteem A	**Duurzaam waterstofsysteem B**	**Huidige aardgassysteem**
Korting op energierekening	€145 per jaar	€145 per jaar	€0,-
Aantal uur per jaar: - Hoogte temperatuur & - Aantal kamers verwarmd	10 uur per jaar geldt: - De maximale temperatuur in uw huis is 21°C & - Alle kamers worden verwarmd	3 uur per jaar geldt: - De maximale temperatuur in uw huis is 17°C & - 1 kamer wordt verwarmd	Er geldt altijd: - De temperatuur in uw huis kunt u zelf bepalen & - Alle kamers worden verwarmd

Welk systeem om uw huis te verwarmen heeft uw voorkeur?

Duurzaam waterstofsysteem A

Duurzaam waterstofsysteem B

Huidig aardgassysteem



Keuze 3 van de 6

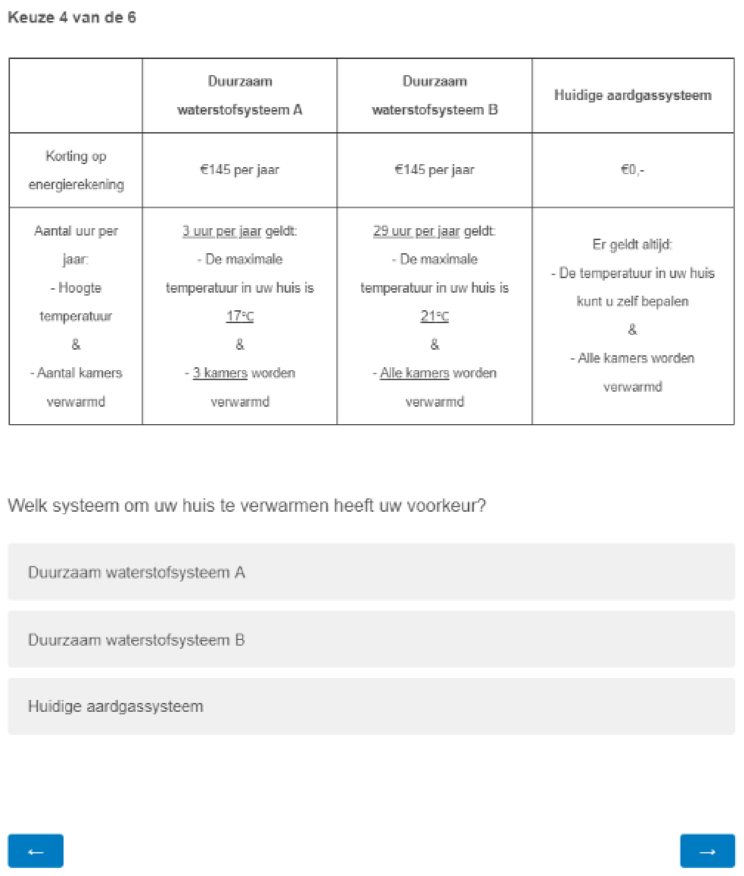
	Duurzaam waterstofsysteem A	Duurzaam waterstofsysteem B	Huidige aardgassysteem
Korting op energierekening	€80 per jaar	€210 per jaar	€0,-
Aantal uur per jaar: - Hoogte temperatuur & - Aantal kamers verwarmd	3 uur per jaar geldt: - De maximale temperatuur in uw huis is 19°C & - Alle kamers worden verwarmd	29 uur per jaar geldt: - De maximale temperatuur in uw huis is 19°C & - 1 kamer wordt verwarmd	Er geldt altijd: - De temperatuur in uw huis kunt u zelf bepalen & - Alle kamers worden verwarmd

Welk systeem om uw huis te verwarmen heeft uw voorkeur?

Duurzaam waterstofsysteem A

Duurzaam waterstofsysteem B

Huidige aardgassysteem



Keuze 4 van de 6

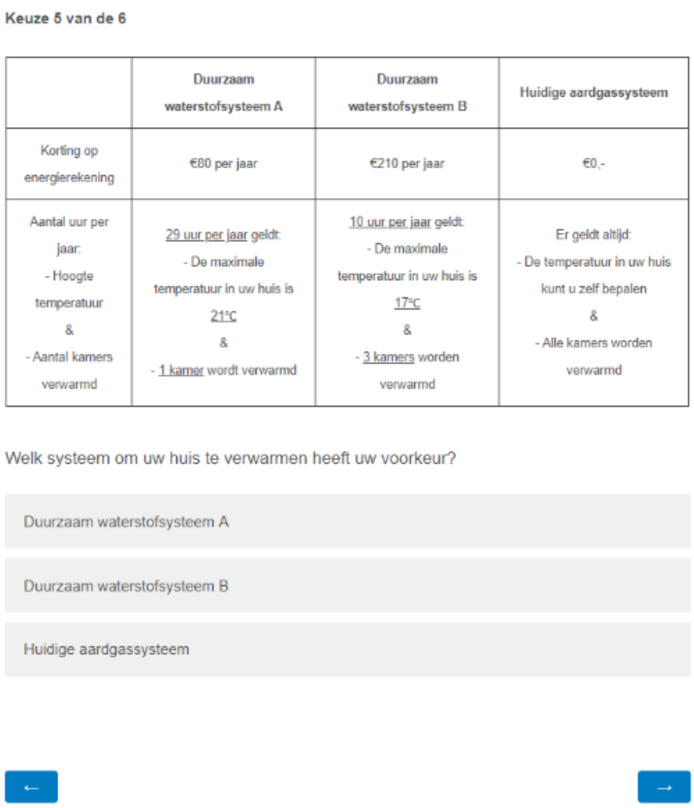
	Duurzaam waterstofsysteem A	Duurzaam waterstofsysteem B	Huidige aardgassysteem
Korting op energierekening	€145 per jaar	€145 per jaar	€0,-
Aantal uur per jaar: - Hoogte temperatuur & - Aantal kamers verwarmd	3 uur per jaar geldt: - De maximale temperatuur in uw huis is 17°C & - 3 kamers worden verwarmd	29 uur per jaar geldt: - De maximale temperatuur in uw huis is 21°C & - Alle kamers worden verwarmd	Er geldt altijd: - De temperatuur in uw huis kunt u zelf bepalen & - Alle kamers worden verwarmd

Welk systeem om uw huis te verwarmen heeft uw voorkeur?

Duurzaam waterstofsysteem A

Duurzaam waterstofsysteem B

Huidige aardgassysteem



Keuze 5 van de 6

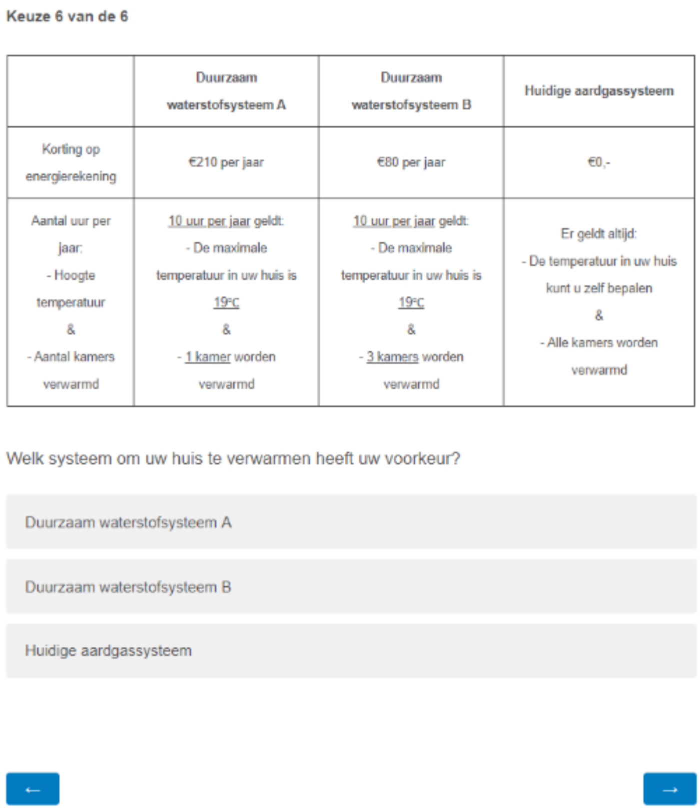
	Duurzaam waterstofsysteem A	**Duurzaam waterstofsysteem B**	**Huidige aardgassysteem**
Korting op energierekening	€80 per jaar	€210 per jaar	€0,-
Aantal uur per jaar: - Hoogte temperatuur & - Aantal kamers verwarmd	29 uur per jaar geldt: - De maximale temperatuur in uw huis is 21°C & - 1 kamer wordt verwarmd	10 uur per jaar geldt: - De maximale temperatuur in uw huis is 17°C & - 3 kamers worden verwarmd	Er geldt altijd: - De temperatuur in uw huis kunt u zelf bepalen & - Alle kamers worden verwarmd

Welk systeem om uw huis te verwarmen heeft uw voorkeur?

Duurzaam waterstofsysteem A

Duurzaam waterstofsysteem B

Huidige aardgassysteem



Keuze 6 van de 6

	Duurzaam waterstofsysteem A	**Duurzaam waterstofsysteem B**	**Huidige aardgassysteem**
Korting op energierekening	€210 per jaar	€80 per jaar	€0,-
Aantal uur per jaar: - Hoogte temperatuur & - Aantal kamers verwarmd	10 uur per jaar geldt: - De maximale temperatuur in uw huis is 19°C & - 1 kamer worden verwarmd	10 uur per jaar geldt: - De maximale temperatuur in uw huis is 19°C & - 3 kamers worden verwarmd	Er geldt altijd: - De temperatuur in uw huis kunt u zelf bepalen & - Alle kamers worden verwarmd

Welk systeem om uw huis te verwarmen heeft uw voorkeur?

Duurzaam waterstofsysteem A

Duurzaam waterstofsysteem B

Huidige aardgassysteem

Appendix F – Data cleaning

The steps taken to clean the data are:

- The unfinished surveys are removed. Only the data from surveys that is completed is considered in this research.

- The missing values were replaced to use the data in Biogeme. The missing values were replaced by the default code of Biogeme for missing values 9999. This was done for missing values for income, gender, educational level and building year.

- In some questions there was the "other, namely" category. The answers filled in were examined and it there was looked whether the answers could fit in the already existing categories, whether another category should be made or whether it would not be included. Sometimes non-existing words were entered. These answers were marked as missing values.

- For all living areas entered by the respondents it was checked whether to consider as city or as village. The value of 25.000 inhabitants was used reference value. All living areas with more than 25.000 inhabitants are considered as cities and living areas with less than 25.000 inhabitants are considered as villages.

- The houses build after 1990 are considered as newbuild homes, since in 1990 the building code is implemented and buildings need to be constructed according to the specified guidelines. These buildings have better insulation and the heating costs are a lot lower than older buildings (Rijksoverheid, 2020).

- Attribute levels for the alternative of the natural gas (base) alternative is added. The levels added are:
  - Cost reduction = €0 per year
  - Time of constraints = 0 hours per year
  - Maximum indoor temperature = 23°C
  - Amount of rooms heated = All rooms

Appendix G – Exploratory Factor Analysis

Within this Appendix the results of the exploratory factor analysis is presented. First, some descriptive results of all the attitudinal statements are shown in Table G.1.

Table G.1 - Descriptive results attitudes

	N	Min	Max	Mean	Std. Error	Std. Dev.
ST1: Sustainability important	411	1	7	5,81	0,062	1,266
ST2: Willing to cut-off natural gas	411	1	7	5,27	0,084	1,707
ST3: Willing to heat with hydrogen	411	1	7	5,17	0,083	1,689
ST4: Willing to heat with electricity	411	1	7	4,82	0,093	1,899
ST5: Willing to heat with green gas	411	1	7	3,85	0,095	1,929
ST6: Willing to use heating system	411	1	7	4,39	0,097	1,981
ST7: Expectation hydrogen is safe	411	1	7	4,96	0,069	1,404
ST8: Expectation hydrogen is expensive	411	1	7	4,47	0,059	1,192
ST9: Expectation hydrogen is reliable	411	1	7	4,77	0,067	1,371
ST10: Expectation Hydrogen 100% CO2 reduction	411	1	7	4,38	0,076	1,552
ST11: Renovation should be in short time	411	1	7	4,79	0,079	1,552

When performing the factor analysis, different chooses are made.

- The principal axis factoring method is used as extracted method, the eigenvalues greater than 1 should be extracted and the correlation matrix is used;
- The “oblimin” rotation method is used, since it is expected that the attitudes are correlated;
- The missing values are excluded listwise.

The KMO and Barlett’s Test is performed to check whether the data is suitable for the exploratory factory analysis. The outcome shows that the data is suitable, the KMO is bigger than 0.5 and the Barlett’s test shows significance. The outcome is displayed in Table G.2.

Table G.2 - KMO and Barlett’s Test

Kaiser-Meyer-Olkin Measure of Sampling Adequacy		0,820
Barlett’s Test of Sphericity	Approx. Chi-Square	1669,418
	Df	55
	Sig.	0.000

The factor analysis displays the scree plot with the eigenvalues of the factors. As a rule of thumb it is used that the eigenvalue should be bigger than 1 and the component where the line flattens out should not be accepted. Based on these criteria 3 factors should be included. The scree plot is displayed in Figure G.1.

In the end, not all the variables score higher than 0.5 on the latent factors. However, after the elimination of the factors that have a lower score on the latent factors, a less beneficiary loading arises on the latent factors. Therefore, it is chosen to keep the variables that score not very high on the latent factors. Furthermore, the loading of these factors is far above the minimum of 0.3.

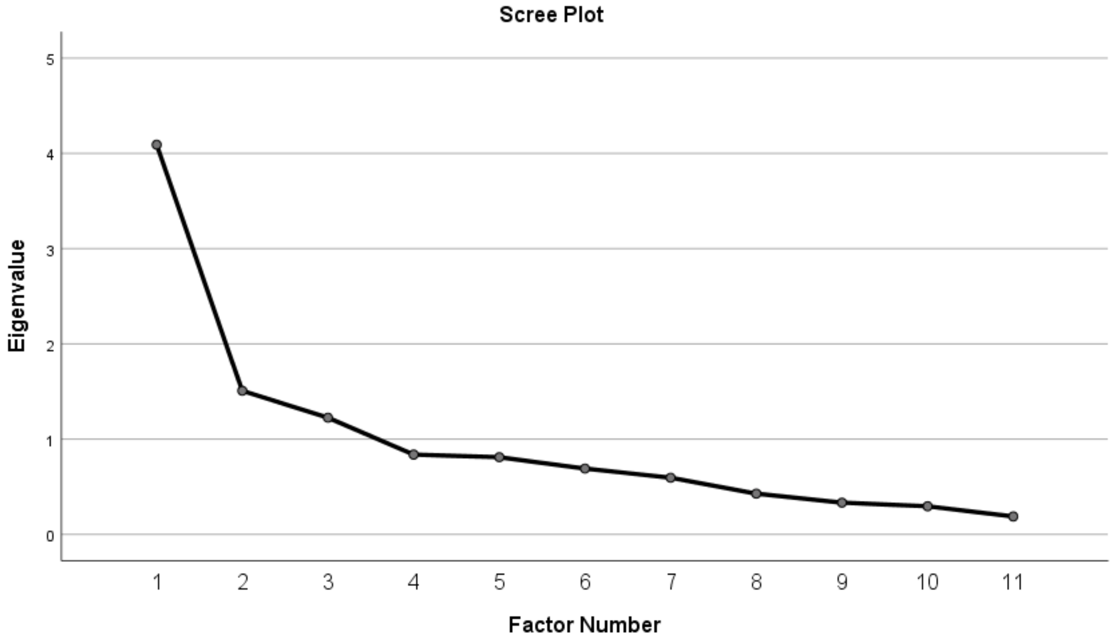


Figure G.1 - Scree plot

In Table G.3 below, the communalities of the variables is displayed. The communalities show the proportion of the variable it's variance that can be explained by the factors. It is defined as the sum of squared factor loading of the variables. The initial values are the squared multiple correlation of one variable with the other variables. The extraction values are the proportion of the variable variance that is explained by the latent factors. A higher value means that the variable is very well represented by the factor, while a low value indicate that the variable is not well represented.

Table G.3 – Communalities of attitudinal variables

	Initial	**Extraction**
ST1: Sustainability important	0,439	0,426
ST2: Willing to cut-off natural gas	0,718	0,811
ST3: Willing to heat with hydrogen	0,676	0,729
ST4: Willing to heat with electricity	0,548	0,600
ST5: Willing to heat with green gas	0,212	0,229
ST6: Willing to use heating system	0,382	0,450
ST7: Expectation hydrogen is safe	0,556	0,680
ST8: Expectation hydrogen is expensive	0,096	0,168
ST9: Expectation hydrogen is reliable	0,529	0,659
ST10: Expectation Hydrogen 100% CO2 reduction	0,199	0,210
ST11: Renovation should be in short time	0,084	0,240

Finally, when looking at the total variance that is explained by the latent factors, it can be seen that the cumulative percentage of the initial eigenvalues of factor 1, 2 and 3 is 62,029%. The three factors explain 62% of the variance.

Appendix H – Representativity

This Appendix display the tests that are performed to analyse whether the sample is representative for the Dutch population. This is done for the characteristics gender, age, income and education level. The Chi-Square test is used to test whether the distributions of the characteristics of the sample are significantly different from the total population. A significant Chi-Square means that the null-hypothesis should be accepted and that the sample significantly differs from the population.

- ***Gender***

The population characteristics for gender are retrieved from CBS Statline (CBS Statline, 2019a).

Table H.1 - Statistics gender

	% Population	% Sample	Observed	Expected	Obs-Exp	$(\text{Obs-Exp})^2$	$(\text{Obs-Exp})^2/\text{Exp}$
Male	49,70%	72%	294	202	92	8413	41,59
Female	50,30%	28%	113	205	-92	8413	41,09
Prefere not to answer			4				
Total Male/Female			407				

Table H.2 - Chi-square test gender

Chi-square value	**82,68**
Df	1
P	9,6E-20

- ***Age***

The population characteristics for age are retrieved from CBS Statline (CBS Statline, 2019a; CBS, 2019).

Table H.3 - Statistics age

	% Population	% Sample	Observed	Expected	Obs-Exp	$(\text{Obs-Exp})^2$	$(\text{Obs-Exp})^2/\text{Exp}$
18-25 years old	10,90%	9%	35	45	10	96	2,14
26-45 years old	30,60%	25%	101	126	25	613	4,88
46-65 years old	34,80%	41%	169	143	-26	675	4,72
66-80 years old	18,10%	24%	97	74	-23	511	6,87
80+ years old	5,70%	2%	9	23	14	208	8,88
Total			411				

Table H.4 - Chi-square test age

Chi-square value	**27,49**
Df	4
P	1,6E-05

- *Income level*

The population characteristics for the income levels are retrieved from CBS Statline (CBS Statline, 2019b).

Table H.5 - Statistics income

Income	% Population	% Sample	Observed	Expected	Obs-Exp	(Obs-Exp)^2	(Obs-Exp)^2/Exp
Less than €10.000 per year	13%	5%	15	41	-26	680	16,56
€10.000 - €20.000 per year	21,90%	4%	14	69	-55	3047	44,04
€20.000 - €30.000 per year	15,80%	11%	35	50	-15	223	4,46
€30.000 - €40.000 per year	12,60%	11%	35	40	-5	23	0,58
€40.000 - €50.000 per year	8,80%	10%	33	28	5	27	0,97
€50.000 - €100.000 per year	12,80%	42%	133	40	93	8566	211,77
More than €100.000 per year	2,30%	16%	51	7	44	1912	263,14
Total			316				
Unknown			95				

Table H.6 - Chi-square test income

Chi-square value	541,52
Df	7
P	9,5E-114

- *Education level*

The population characteristics for education levels are retrieved from CBS Statline (CBS, 2018).

Table H.7 - Statistics education level

Education	% Population	% Sample	Observed	Expected	Obs-Exp	(Obs-Exp)^2	(Obs-Exp)^2/Exp
Primary	9%	1%	6	37	-31	960	25,96
High school & MBO	60%	25%	102	247	-145	20909	84,79
HBO & WO	30%	72%	295	123	172	29481	239,10
Unknown	1%	2%	8	4	4	15	3,68
Total			411				

Table H.8 - Chi-square test education level

Chi-square value	541,52
Df	7
P	9,5E-114

From the tables H.1 – H.8 it can be concluded that the Chi-Square is significant on the characteristics gender, age, income and education level. Therefore, the sample is significantly different from the population.

Appendix I – Utility functions

The systematic utility functions of the base MNL model for the three alternatives are:

$$V_{HydrogenA} = ASC_{Hydrogen} + \beta_{Cost} * CostA + \beta_{Time} * TimeA + \beta_{Temp} * TempA + \beta_{Room1} * RoomA1 + \beta_{Room2} * RoomA2$$

$$V_{HydrogenB} = ASC_{Hydrogen} + \beta_{CostB} * CostB + \beta_{TimeB} * TimeB + \beta_{TempB} * TempB + \beta_{Room1} * RoomB1 + \beta_{Room2} * RoomB2$$

$$V_{Naturalgas} = \beta_{CostC} * CostC + \beta_{TimeC} * TimeC + \beta_{TempC} * TempC + \beta_{Room1} * RoomC1 + \beta_{Room2} * RoomC2$$

The systematic utility functions of the base MNL model with quadratic components for the three alternatives are:

$$V_{HydrogenA} = ASC_{Hydrogen} + \beta_{Cost} * CostA + (\beta_{Cost})^2 * CostA + \beta_{Time} * TimeA + (\beta_{Time})^2 * TimeA + \beta_{Temp} * TempA + (\beta_{Temp})^2 * TempA + \beta_{Room1} * RoomA1 + \beta_{Room2} * RoomA2$$

$$V_{HydrogenB} = ASC_{Hydrogen} + \beta_{Cost} * CostB + (\beta_{Cost})^2 * CostB + \beta_{Time} * TimeB + (\beta_{Time})^2 * TimeB + \beta_{Temp} * TempB + (\beta_{Temp})^2 * TempB + \beta_{Room1} * RoomB1 + \beta_{Room2} * RoomB2$$

$$V_{Naturalgas} = \beta_{Cost} * CostC + (\beta_{Cost})^2 * CostC + \beta_{Time} * TimeC + (\beta_{Time})^2 * TimeC + \beta_{Temp} * TempC + (\beta_{Temp})^2 * TempC + \beta_{Room1} * RoomC1 + \beta_{Room2} * RoomC2$$

The systematic utility functions of the error component (preference) panel ML model for the three alternatives are:

$$V_{HydrogenA} = ASC_{Hydrogen} + \upsilon_{n,hydrogen} + \beta_{Cost} * CostA + \beta_{Time} * TimeA + \beta_{Temp} * TempA + \beta_{Room1} * RoomA1 + \beta_{Room2} * RoomA2 + \beta_{CostTempD} * CostA * TempD + \beta_{CostIns1} * CostA * Ins1 + \beta_{CostIns2} * CostA * Ins2 + \beta_{CostIns} * CostA * Ins + \beta_{CostSUS} * CostA * SUS + \beta_{CostTM} * CostA * TM + \beta_{Own} * Own + \beta_{SUS} * SUS + \beta_{HYD} * HYD$$

$$V_{HydrogenB} = ASC_{Hydrogen} + \upsilon_{n,hydrogen} + \beta_{Cost} * CostB + \beta_{Time} * TimeB + \beta_{Temp} * TempB + \beta_{Room1} * RoomB1 + \beta_{Room2} * RoomB2 + \beta_{CostTempD} * CostB * TempD + \beta_{CostIns1} * CostB * Ins1 + \beta_{CostIns2} * CostB * Ins2 + \beta_{CostIns} * CostB * Ins + \beta_{CostSUS} * CostB * SUS + \beta_{CostTM} * CostB * TM + \beta_{Own} * Own + \beta_{SUS} * SUS + \beta_{HYD} * HYD$$

$$V_{Naturalgas} = \beta_{Cost} * CostA + \beta_{Time} * TimeC + \beta_{Temp} * TempC + \beta_{Room1} * RoomC1 + \beta_{Room2} * RoomC2 + \beta_{CostTempD} * CostC * TempD + \beta_{CostIns1} * CostC * Ins1 + \beta_{CostIns2} * CostC * Ins2 + \beta_{CostIns} * CostC * Ins + \beta_{CostSUS} * CostC * SUS + \beta_{CostTM} * CostC * TM$$

Where,
$\upsilon_{n,Hydrogen} \sim N(0, \sigma_{\upsilon_{Hydrogen}})$

The systematic utility functions of the taste panel ML model for the three alternatives are:

$$V_{HydrogenA} = ASC_{Hydrogen} + \beta_{n,Cost} * CostA + \beta_{n,Time} * TimeA + \beta_{n,Temp} * TempA + \beta_{n,Room1} * RoomA1 + \beta_{n,Room2} * RoomA2 + \beta_{CostTempD} * CostA * TempD + \beta_{CostIns1} * CostA * Ins1 + \beta_{CostIns2} * CostA * Ins2 + \beta_{CostIns} * CostA * Ins + \beta_{CostSUS} * CostA * SUS + \beta_{CostTM} * CostA * TM + \beta_{Own} * Own + \beta_{SUS} * SUS + \beta_{HYD} * HYD$$

$$V_{HydrogenB} = ASC_{Hydrogen} + \beta_{n,Cost} * Cost + \beta_{n,Time} * TimeB + \beta_{n,Temp} * TempB + \beta_{n,Room1} * RoomB1 + \beta_{n,Room2} * RoomB2 + \beta_{CostTempD} * CostB * TempD + \beta_{CostIns1} * CostB * Ins1 + \beta_{CostIns2} * CostB * Ins2 + \beta_{CostIns} * CostB * Ins + \beta_{CostSUS} * CostB * SUS + \beta_{CostTM} * CostB * TM + \beta_{Own} * Own + \beta_{SUS} * SUS + \beta_{HYD} * HYD$$

$$V_{Naturalgas} = \beta_{n,Cost} * CostC + \beta_{n,Time} * TimeC + \beta_{n,Temp} * TempC + \beta_{n,Room1} * RoomC1 + \beta_{n,Room2} * RoomC2 + \beta_{CostTempD} * CostC * TempD + \beta_{CostIns1} * CostC * Ins1 + \beta_{CostIns2} * CostC * Ins2 + \beta_{CostIns} * CostC * Ins + \beta_{CostSUS} * CostC * SUS + \beta_{CostTM} * CostC * TM$$

Where,
$\beta_{n,Cost} \sim N(\beta_{Cost}, \sigma_{\beta_{Cost}})$
$\beta_{n,Time} \sim N(\beta_{Time}, \sigma_{\beta_{Time}})$
$\beta_{n,Temp} \sim N(\beta_{Temp}, \sigma_{\beta_{Temp}})$
$\beta_{n,Room1} \sim N(\beta_{Room1}, \sigma_{\beta_{Room1}})$
$\beta_{n,Room2} \sim N(\beta_{Room2}, \sigma_{\beta_{Room2}})$

Appendix J – Model fit

This Appendix shows the model fit of the different models.

The model fit of both the MNL models is displayed in Table J.1.

Table J.1 - Model fit MNL

	Parameters	Rho-Square	Final LL	LRS
Null model	0	-	-2709,178	-
Base MNL model	6	0,083	-2483,037	452,281
Final extended MNL model	15	0,229	-2088,686	1240,984

The Rho-Square of both models can be compared to analyze which model fits the data better. The values are displayed in Table J.1. The value results in the percentage of the initial uncertainty that is explained by the model (Chorus, 2018). The Rho-Square of the extended MNL model implies that 22,3% of the initial uncertainty is explained by the model, while only 8,3% of the initial uncertainty is explained by the base MNL model.

Besides comparing the Rho-Square, the likelihood ratio test can also be used to test whether the extended MNL model fits the data better than the base MNL model. The LRS of the MNL is compared to the extended MNL by the following formula:

$$LRS = -2 * (LL_{MNL\ base} - LL_{MNL\ extended}) = -2 * (-2483{,}037 - -2088{,}686) = 788{,}702$$

The difference in parameters between the base MNL and the extended MNL is 9, so the degrees of freedom are 9. The critical chi-square at a 1% significance level is 21,666. The LRS value is higher than this critical value, which implies that the extended MNL model fits the data better than the base MNL model. Moreover, the Adjusted Rho-Square of the extended MNL model is higher. This results that the extended MNL model fits the data better than the base MNL base model.

The model fit of the ML models can be seen in Table J.2.

Table J.2 - Model fit ML models

	Parameters	Rho-Square	Final LL	LRS
Panel ML error component model	16	0,263	-1742,198	1244,779
Panel ML taste model	20	0,621	-1734,688	5690,990
Combined ML	21	0,678	-1688,475	7243,413

Similar to the comparison of the extended MNL to the base MNL, the ML models are compared to each other based on the LRS. De formulas and calculations are shown below.

$$LRS = -2 * \left(LL_{ML\ error\ component} - LL_{ML\ taste}\right) = -2 * (-1742{,}220 - -1734{,}688) = 15{,}064$$

$$LRS = -2 * (LL_{ML\ taste} - LL_{ML\ combined}) = -2 * (-1734{,}688 - -1688{,}475) = 92{,}426$$

The difference in parameters between the ML error component model and the ML taste model is 4, so the degrees of freedom are four. The critical chi-square at a 1% significance level is 13,28. The difference in LRS value is above this critical value. Concludingly, the ML taste model fits the data better than the ML Error Component. Therefore, the Combined ML model is compared to the ML taste preference model. The degree of freedom is one. The critical chi-square at a 1% significance level is 6,63. Again the LRS value is above this critical value. Concludingly, the combined ML model fits the data better than the other ML models and is compared in the next chapter with the extended MNL model. Next to the LRS value, it can be seen that both the sigma for the unobserved as for the observed heterogeneity is significant. This implies that both forms of heterogeneity should be considered and that the combined ML model will fit the data better than the other two combined ML models. Lastly, when comparing the Rho-Square value of all three models, it can be seen that the most initial uncertainty is explained by the Combined ML model, namely 67,8%.

Finally, the model fit of all the models is displayed in Table J.3.

Table J.3 - Model fit MNL and ML models

	Parameters	Rho-Square	Final LL	LRS
Null model	0	-	-2709,178	-
Base MNL model	6	0,083	-2483,037	452,281
Final extended MNL model	15	0,229	-2088,686	1240,984
Panel ML error component model	16	0,263	-1742,198	1244,779
Panel ML taste model	20	0,621	-1734,688	5690,990
Combined ML	21	0,678	-1688,475	7243,413

The model fit of the combined ML model is compared to the extended MNL model. First, the Rho-Square test is considered. It can be seen that the combined ML model explains away 67,8% of the initial uncertainty, while the extended MNL model explains 22,3% of the initial uncertainty.

Next to the Rho-Square test, the likelihood ratio test can also help to determine whether the combined ML model fits the data better than the extended MNL model. The LRS of the combined ML model is compared to the extended MNL by the following formula:

$$LRS = -2 * (LL_{MNL\ extended} - LL_{ML\ combined}) = -2 * (-2088{,}686 - -1702{,}170) = 773{,}032$$

The difference in parameters between the extended MNL model and the combined ML model is 6, so the degrees of freedom are 6. The critical chi-square at a 1% significance level is 16,81. The LRS value is far above this value. This implies that the combined ML model fits the data better than the extended MNL model.

Appendix K – Parameter estimates ML models

This Appendix displays the parameter estimates of the panel error component ML model (table K1), the panel taste ML model(table K1), and the combined ML model (table K2). All the outcomes are estimates based on 200 runs.

Table K.1 - Parameter estimates ML error component model and ML taste model 200 draws

Variables	**ML Error Component** *(200 runs)*			**ML Taste** *(200 runs)*		
	Value	Std. error	P-value	Value	Std. error	P-value
ASC_Hydrogen	-7,97	1,24	0,00	-3,38	0,843	0,00
Beta_Cost	0,0148	0,00435	0,00	0,00570	0,00613	0,35*
Sigma_Cost	-	-	-	-0,0183	0,00154	0,00
Beta_Room1	-0,573	0,0954	0,00	-0,977	0,139	0,00
Sigma_Room1	-	-	-	1,15	0,210	0,00
Beta_Room2	0,0567	0,0839	0,50*	-0,00948	0,129	0,94*
Sigma_Room2	-	-	-	-0,378	0,166	0,02
Beta_Temp	0,337	0,0213	0,00	0,594	0,0367	0,00
Sigma_Temp	-	-	-	0,391	0,0348	0,00
Beta_Time	-0,0115	0,00329	0,00	-0,0140	0,00434	0,00
Sigma_Time	-	-	-	0,0341	0,00751	0,00
Sigma_Hydrogen	3,65	0,308	0,00	-	-	-
Beta_CostIns	-0,00194	0,000693	0,01	-0,00241	0,000971	0,01
Beta_CostIns1	-0,000375	0,000728	0,61*	-0,00238	-0,000989	0,02
Beta_CostIns2	-0,00214	0,000687	0,00	-0,00175	0,000948	0,07*
Beta_CostSUS	0,00145	0,000566	0,01	0,00267	0,000807	0,00
Beta_CostTempD	-0,00268	0,000432	0,00	-0,00194	0,000585	0,00
Beta_CostVAL	-0,00154	0,000660	0,02	-0,00291	0,000961	0,00
Beta_HYD	0,875	0,174	0,00	0,625	0,123	0,00
Beta_OWN	-0,0672	0,207	0,75*	-0,000413	0,145	1,00*
Beta_SUS	1,33	0,193	0,00	0,771	0,138	0,00
*Not significant at a 95% significance level						

Table K.2 - Parameter estimates ML combined model 200 draws

Variables	**ML Combined** *(200 runs)*		
	Value	Std. error	P-value
ASC_Hydrogen	-6,08	1,32	0,00
Beta_Cost	0,0128	0,00624	0,004
Sigma_Cost	-0,0127	0,00141	0,00
Beta_Room1	-0,747	0,140	0,00
Sigma_Room1	1,06	0,203	0,00
Beta_Room2	0,0174	0,127	0,89*
Sigma_Room2	0,467	0,229	0,04
Beta_Temp	0,0557	0,0404	0,00
Sigma_Temp	0,398	0,0413	0,00

Beta_Time	-0,0128	0,00440	0,00
Sigma_Time	0,0153	0,00671	0,02
Sigma_Hydrogen	-4,00	0,362	0,00
Beta_CostIns	-0,00257	0,000964	0,01
Beta_CostIns1	-0,000276	0,00102	0,79*
Beta_CostIns2	-0,00259	0,000980	0,01
Beta_CostSUS	0,00214	0,000836	0,01
Beta_CostTempD	-0,00293	0,000604	0,00
Beta_CostVAL	-0,00165	0,000956	0,08*
Beta_HYD	0,917	0,166	0,00
Beta_OWN	0,0237	0,196	0,90*
Beta_SUS	1,21	0,218	0,00
*Not significant at a 95% significance level			

Table K.3 shows the estimation results for the combined model were the cost parameter is fixed. These estimations are used for the calculations of the Willingness To Pay (WTP). The outcomes are the result of 1200 Halton draws.

Table K.5 - ML Combined fixed costs

Variables	**ML Combined fixed cost** *(800 runs)*		
	Value	Std. error	P-value
ASC_Hydrogen	-7.64	1.27	0,00
Beta_Cost	0.0149	0.00469	0,01
Sigma_Cost	-	-	-
Beta_Room1	-0.454	0.110	0,00
Sigma_Room1	0.624	0.185	0,00
Beta_Room2	0.146	0.107	0,17*
Sigma_Room2	0.820	0.144	0,00
Beta_Temp	0.466	0.0354	0,00
Sigma_Temp	0.279	0.0428	0,00
Beta_Time	-0.00888	0.00383	0,02
Sigma_Hydrogen	-3.76	0.338	0,00
Beta_CostIns	-0.00209	0.000738	0,01
Beta_CostIns1	-0.000484	0.000774	0,53*
Beta_CostIns2	-0.00228	0.000729	0,00
Beta_CostSUS	0.00160	0.000621	0,01
Beta_CostTempD	-0.00263	0.000458	0,00
Beta_CostVAL	-0.00186	0.00708	0,01
Beta_HYD	0.932	0.176	0,00
Beta_OWN	-0.0373	0.200	0,85*
Beta_SUS	1.32	0.194	0,00
*Not significant at a 95% significance level			

Appendix L – Influence explanatory factors on WTP estimates

Insights in gas use

This section estimates the interaction between the insights in the gas use and the cost reduction attribute. The effect on the cost reduction of the households without insights into their gas use is estimated by 0,0149 + -1 * -0,00209 = 0,01699. For households with insights into their gas use, the influence of the cost reduction on the utility will become 0,0149 + 1 * -0,00209 = 0,01281. Table L.1 shows the influence of the insights in the gas used on the WTP for the different reliability attributes, and in square brackets, the 95%-confidence interval is given. The numbers estimated are rounded up.

Table L.1 - WTP based on insights in gas use

	Mean WTP for households with insights	**Mean WTP for households without insights**
Time constraint *(€/hour decrease)*	€0,70 (+€0,10)	€0,50 (-€0,10)
Indoor temperature *(€/°C increase)*	€36 [-€6;€79] (+ €5)	€27 [-€5;€60] (- €4)
All rooms instead of one room *(€)*	€35 [-€60;€60] (+ €5)	€26 [-€45;€99] (- €4)

Based on Table L.1, one can conclude that households with insights in their gas demand have a higher WTP for the reliability attributes, especially compared to households with no insights in their gas demand. Probably the fact that the households with insights into their gas use are aware of the cost and their energy usage causes this effect. They know how to reduce their cost.

Figure L.1 displays the distribution of respondents that do and do not have insights into their gas use. The distribution is not equal and a lot more respondents filled in the survey with insights into their gas use than respondents without insights—however, 60 respondents without insights filled in the survey, which should be enough to conclude.

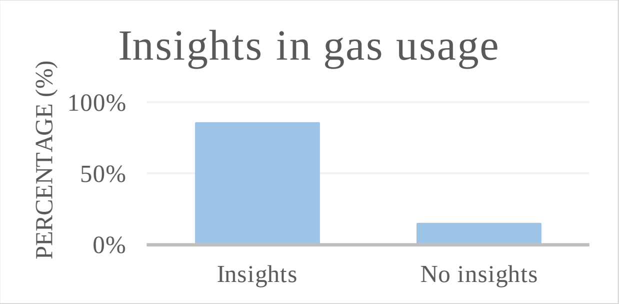


Figure L.1 - Distribution of insight in gas usage

Insulation of house

The cost reduction for households living in well-insulated houses on the utility of the alternative is estimated by 0,0149 + -1 * -0,00228 = 0,01718. The interaction for less insulated houses is 0,01262. Table L.2 shows the estimations of the WTP, within square brackets, the 95%-confidence interval.

Table L.2 - WTP based on the insulation of a house

	Mean WTP (well-insulated)	**Mean WTP (less-insulated)**
Time constraint *(€/hour decrease)*	€0,50 (- €0,10)	€0,70 (+ €0,10)
Indoor temperature *(€/°C increase)*	€27 [-€5;€59] (- €3)	€37 [-€6;€80] (+ €6)
All rooms instead of one room *(€)*	€26 [-€45;€80] (- €4)	€35 [-€61;€133] (+ €5)

From Table L.2, it can be seen that households living in well-insulated houses have, on average, a lower Willingness To Pay (WTP) for reliability. The lower WTP becomes especially visible when this group is compared to households living in houses with only a few insulation measures taken.

Figure L.2 displays the deviation of respondents based on the number of insulation measures. Based on this figure, one can conclude that there are slightly fewer respondents that have taken lots of measures to insulate. The Figure also displays that 1/3 of the respondents took no/limited insulation measures.

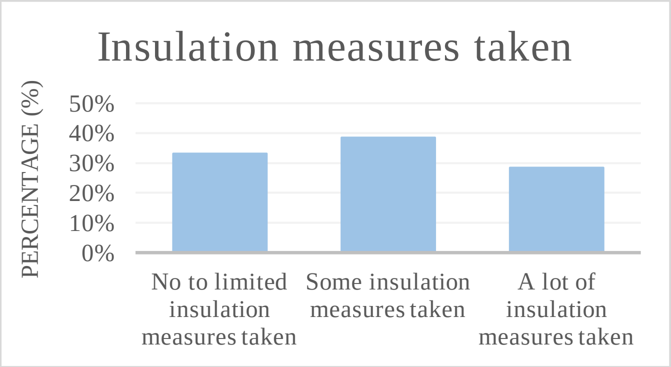


Figure L.2 - Distribution of insulation measures

The expectation of using sustainable heating

The influence of the expectation of using sustainable heating is calculated by multiplying the parameter estimate beta_CostSUS with the number 1 to 7. The number one implies that someone does not expect to use sustainable heating, and the number seven implies that someone definitely expects to use sustainable heating. The outcomes are added to the estimate for cost reduction to determine the influence on the Willingness To Pay. Table L.3 displays the influence on the WTP for different attitudes. This research did not add the confidence interval, since the WTP estimates only decrease. Therefore, it is sure to state that the gap between cost and reliability will increase.

Table L.3 - WTP based on the expectation to use sustainable heating

	1	**2**	**3**	**4**	**5**	**6**	**7**
Time *(€/hour decrease)*	€0,55 (-€0,05)	€0,50 (-€0,10)	€0,45 (-€0,15)	€0,40 (-€0,20)	€0,40 (-€0,20)	€0,35 (-€0,25)	€0,35 (-€0,25)
Temp *(€/°C increase)*	€28 (-€3)	€26 (-€4)	€24 (-€7)	€22 (-€9)	€20 (-€11)	€19 (-€12)	€18 (-€13)
All rooms iso 1 room *(€)*	€28 (-€2)	€25 (-€5)	€23 (-€7)	€21 (-€9)	€20 (-€11)	€19 (-€12)	€17 (-€13)

Table L.3 shows that the households that expect to use sustainable heating have, on average, a lower WTP for all reliability attributes. For this group, all the estimates are below the current cost of energy.

Table L.3 displays the distribution of the different attitudes in the sample. From this figure, one can conclude that most respondents are neutral to very positive about their expectation of using sustainable heating. The respondents that really expect that they will use sustainable heating are, however, the lowest from these four groups.

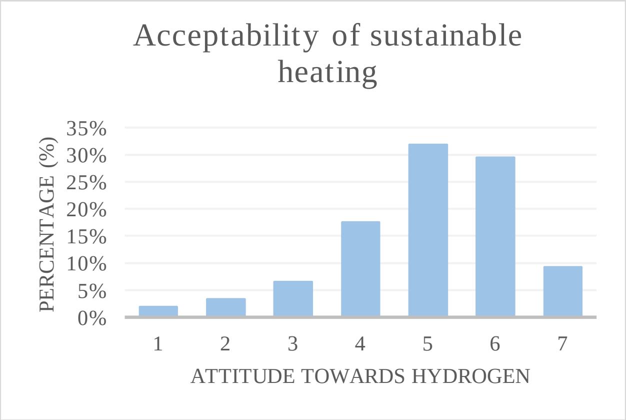


Figure L.3 - Distribution of expectation of using sustainable heating

Maintained indoor temperature

The maintained indoor temperature significantly influences the Willingness To Pay (WTP) for reliability. The effect is calculated in the same way as the acceptability of sustainable heating. The parameter estimate for beta_CostTempD is multiplied with the coding for the different indoor temperatures. Table L.4 displays the estimations.

Table L.4 - Interaction effect of different maintained indoor temperatures

TempD	**ML**
<16°C	0,0149 + -0,00263 * 0 = 0,0149
16 - 17°C	0,0149 + -0,00263 * 1 = 0,01227
17 - 18°C	0,0149 + -0,00263 * 2 = 0,00964
18 - 19°C	0,0149 + -0,00263 * 3 = 0,00701
19 – 20°C	0,0149 + -0,00263 * 4 = 0,00438
20 - 21°C	0,0149 + -0,00263 * 5 = 0,00175
21 - 22°C	*0,0149 + -0,00263 * 6 = -0,00088*
22 - 23°C	*0,0149 + -0,00263 * 7 = -0,00351*
>23°C	*0,0149 + -0,00263 * 8 = -0,00614*

After an indoor temperature of 21 - 22°C, the interaction effect becomes negative. The negative interaction effect implies that households maintaining a higher temperature than 21°C have a dislike for a cost reduction. This research estimates the WTP of the households maintaining a lower indoor temperature than 21°C. Since households maintaining an average indoor temperature above the 21°C dislike a cost reduction, no accurate estimations about the WTP can be given. Table L.5 displays the mean WTP estimations. This research did not add the confidence interval since no one can steer the preferred indoor temperature. The variable explains the heterogeneity of the WTP.

Table L.5 - WTP based on maintained indoor temperature

	< 16°C	**16-17°C**	**17-18°C**	**18-19°C**	**19-20°C**	**20-21°C**
Time constraint *(€/hour decrease)*	€0,60 (€0)	€0,70 (+€0,10)	€1 (+€0,40)	€1,30 (+€ 0,70)	€2 (+€1,4)	€5 (+€5,40)
Indoor temperature *(€/°C increase)*	€31 (€0)	€38 (+€7)	€48 (+€17)	€66 (+€35)	€106 (+€75)	€266 (+€235)
All rooms iso 1 room	€30 (€0)	€37 (+€7)	€47 (+€17)	€65 (+€35)	€104 (+€74)	€259 (+€229)

Table L.5 shows that the indoor temperature maintained indoor has a significant influence on the WTP for the reliability of the system used for heating. The households that maintain a higher indoor temperature are average willing to pay a lot more for reliability than the households that maintain a lower indoor temperature. A significant difference in the WTP between households that maintain an indoor temperature of 18-19°C, 19-20°C, and 20-21°C is estimated. For households maintaining an indoor temperature of 19-20°C, there seems still a small gap between their WTP and the cost. For households maintaining a temperature of 20-21°C, there seems to be no gap between the WTP and de cost. Furthermore, there is a general dislike for reducing the reliability of households that maintain, on average, a higher temperature than 21°C. Figure L.4 shows the distribution of the maintained indoor temperature.

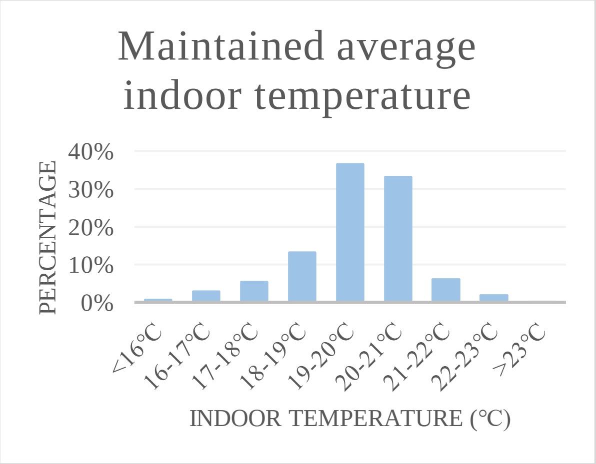


Figure L.4 - Distribution of maintained indoor temperature

Appendix M – Scientific paper

The trade-off between reliability and affordability of a hydrogen grid from the perspective of households

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Abstract The built environment needs to become completely sustainable before 2050. Hydrogen is seen as a suitable resource to help in achieving this goal. In a hydrogen system, the predefined high level of reliability, as stands today, affects the affordability of the system. The households are the users and payers of the system. This research identifies a gap between the Willingness To Pay (WTP) for reliability and the current cost of this level of reliability. Reliability should not be a goal on its own. The maintained level of reliability should be optimized together with the affordability of the system.

Keywords: Hydrogen infrastructure; Affordability; Reliability; Discrete Choice Modeling; Households.

1. Introduction

One of the essential sustainable development goals is to ensure access to affordable, reliable, and sustainable energy [1]. To ensure the sustainability goal, the energy transition in the built environment needs to start [2]. Hydrogen is seen as a suitable resource that can help make the built environment sustainable [2]. Currently, the trade-off between the reliability and the affordability of the system used for heating is primarily determined based on a predefined level of reliability [3][4]. In a hydrogen system used for heating, the predefined high level of reliability affects the affordability of the system. High investment costs need to be made [5]. Reliability concerns the quality of the network [6]. It refers to the ability of the infrastructure to deliver the quantity and quality of energy as demanded by the users [7]. A reliable natural gas infrastructure has continuous delivery without interruptions. A downside of very reliable infrastructures is that it interferes with the affordability of infrastructures.

Brown, et al. [8] point out that very reliable systems cause higher capital and operational costs. Moreover, it is generally accepted to state that the cost of a system is an increasing function of the reliability of the system. Each level of reliability comes with certain costs [9].

Each level of reliability comes with certain costs [9]. From an economic perspective, it is known that too reliable products come with very high costs, while the consumer might opt for less reliable products with lower costs [10]. The households are the users and payers of the system. They are affected by the level of reliability and the associated cost of the energy system. It is important to investigate the preference of the households related to the tradeoff between a reliable and affordable infrastructure used for heating. In the heating domain, it remains untouched what level of reliability is desired by the households against what costs or whether households opt for a less reliable network at lower costs. The understanding and assessment of the trade-off are lacking. Research can give insights into the societal optimum between affordability and reliability and can foster the discussion about the design and regulations of a system used for heating in the Netherlands. Within this research, the term "(energy) consumers" or "public" refer to the households connected to the gas grid. The research question corresponding to the identified problem is:

"What are the preferences of Dutch households in the design of a reliable and affordable green hydrogen grid in the built environment within the service area of Stedin?"

The structure of this paper is as follows. First, a literature study is performed to identify important background information. Then the methodology used to answer the research question is discussed. Section three discusses the results. After that, sections 5 and 6 display the discussion and conclusion. Finally, section 7 gives practical and scientific recommendations.

2. Literature study

In energy systems, there is no one on one relationship between the investment cost of the grid operators and the benefits of the households. This relation is caused by the fact that the gas system is a common-pool resource [11][12]. The users' benefits are related to the Willingness To Pay (WTP) for a reliable energy system [13]. The Willingness To Pay (WTP) is the maximum amount consumers are willing to pay for a product or service. The WTP is a crucial factor when determining the price of products or, as in this research, the reliability. A higher utility or benefit derived from service results in a higher WTP [13]. The WTP for a more reliable energy service decreases when the utility of the user will no longer increase due to better services. The cost of investment for increasing the reliability of energy systems should be economically efficient and not outreach the benefits and the WTP of the users. The grid operators, such as Stedin, are responsible for the investments in the transportation network. They need to maintain a reliable and affordable energy network.

The reliability can be described as "the ability to supply the quantity and quality of energy desired by the customer when it is needed" [14]. A decrease in the reliability of a system does not always lead to a reduction in social welfare. It might even improve the social welfare in case the reliability level is above the appropriate level of reliability. At that moment, the cost to create the level of reliability in the system is considered to be too high [6].

A reliable natural gas infrastructure has continuous delivery without interruptions. The current reliability regulations state that grid operators are obliged to deliver gas to the end households until an average temperature of -12℃ [3][4]. The regional grid operators are obliged to have an operational gas grid that they keep maintaining and developing in a way that the reliability of the grid is ensured [15].

For the production of hydrogen, electrolyers need to be constructed by energy companies. The investment costs depend on the size of the electrolysers. The higher generation capacity of the electrolysers is correlated with higher investment costs. The construction cost for an electrolyser is approximately €12.000.000 €/MW [5][16]. The level of reliability mainly influences the investment costs, whereas it is expected that transportation and production costs will remain almost constant.

The primary purpose of the natural gas used in the residential sectors is space heating. Consequently, natural gas use is strongly related to the outside temperature. In case the level of reliability of the energy system decreases, constraints on the demand side are necessary to make sure the demand does not outreach the supply. The constraints should apply during extremely cold periods. During these periods, the demand will most possibly exceed the supply. This research searches for the average WTP for the reliability of the system used for heating.

3. Methodology

This research uses Discrete Choice Modeling (DCM) to answer the research question identified in the introduction. DCM is used to analyze the choices made by respondents from a set of alternatives. The relative influence of the included attributes of the alternatives can be calculated [17]. In DCM, the Willingness To Pay (WTP) can be calculated as the increase (or decrease) of one unit in utility divided by the change in utility of the price coefficient [18]. By calculating the WTP for reliability, the trade-off between reliability and affordability can be taken into account. A stated choice experiment collects the data for the DCM.

3.1 Stated choice experiment

For data collection, a stated choice experiment is conducted amongst households living in the Netherlands. In the choice experiment, the respondents needed to choose between three alternatives—two hydrogen alternatives with a lower level of reliability and one natural gas alternative. The natural gas system is the opt-out alternative and makes sure the respondents are not forced to choose between two hydrogen alternatives. Each alternative consists of four design variables. The affordability of the system is defined by the cost reduction attribute obtained by a lower level of reliability. The reliability aspect is defined by a period with a maximum indoor temperature in a specified number of rooms.

Table M.1 displays the attributes with the attribute levels incorporated in the design of the hydrogen alternatives. The natural gas system has no cost reduction and no lower level of reliability.

Table M.1 - Attributes and attribute levels

Attributes	**Attribute levels**		
Cost reduction (€/year)	80	145	210
Time with constraints (h/year)	3	10	29
Max indoor temperature (°C)	17	19	23
Amount of rooms heated	1	3	All

The stated choice experiment was constructed by Bayesian efficient factorial design. The priors were estimated based on the paper of Bliemer and Collins (2016)[19]. The software package Ngene was used to create the Bayesian efficient design.

For the design of the stated choice experiment, 12 choice sets were constructed. These choice sets were dived into two blocks. Each respondent needed to make six choices. An example of a choice set shown to the respondent is shown in Table M.2. Besides the choice sets, the questionnaire consisted of questions related to the socio-demographic and economic characteristics of the respondents and asked for heating habits, housing characteristics, and attitudes towards sustainability and hydrogen.

Table M.2 - Example of a choice set

	Hydrogen alternative 1	**Hydrogen alternative 2**	**Natural gas system**
Cost reduction	€210 per year	€80 per year	€0 per year
Hours with constraints	10 hours per year	10 hours per year	0 hours per year
Max indoor temperature	17°C	21°C	No max temperature
Amount of rooms heated	3 rooms	All rooms	All rooms

3.2 Data collection

The data is collected by the Qualtrics survey software. The data is gathered between the 14th of July until the 17th of August 2020. All households living in the Netherlands and older than 18 years old were allowed to fill in the survey. In total 510 respondents started the survey, while 411 respondents completed the whole survey.

The sample that completed the survey was compared to the Dutch population, to determine whether the sample is representative. They are compared based on gender, age, education, and income. Based on this comparison, one can conclude that the sample is unrepresentative for the Dutch population regarding gender, age, educational level, and income. Males are highly overrepresented, while females are underrepresented. The age groups of 56 – 65 and 66 – 80 years old are overrepresented, while the other groups are underrepresented. The high level of education is overrepresented in the sample compared to the population, whereas the middle and low education levels are underrepresented. Finally, the higher income levels of the sample are highly overrepresented, whereas the low-income levels are highly underrepresented compared to the actual income of the population. Concludingly, the sample is biased regarding gender, age, education level, and income. The unrepresentative sample may result in biased parameters. Other biases may occur due to self-selection. Respondents were asked voluntarily to fill in the survey. When analyzing and interpreting the results, it is essential to keep in mind the biases since these might influence the results.

3.3 Data analysis

The most widely used discrete choice model is based upon the Random Utility Maximization (RUM) model. This model is developed by McFadden (1974) [20]. RUM models assume that individuals strive for utility maximization and choose the alternative that maximizes their utility. It assumes the complete rationality of individuals [21]. Within this research, the discrete choice model is based upon the RUM model. The goal of this research is not analyzing the choice behavior of respondents but looks for the average WTP for a system used for heating. With this goal, the behavioral assumption of complete rationality of individuals is not severe and is an appropriate method to calculate the average WTP.

In each choice set, the respondent can choose between three alternatives: sustainable hydrogen system A, sustainable hydrogen system B, and the current natural gas system. Every alternative has its utility function that calculates the utility of the alternative. The utility of an alternative is the sum of the systematic utility and the random utility. The systematic utility is predicted by the parameters included in the discrete choice model.

The observed factors are both the attributes in the choice set as the variables measured in the survey (such as income). The random utility cannot be predicted by the model and is seen as "noise." This utility is captured in the error term and represents the variability of the total utility of the alternative [18]. The choice probabilities display the chance an alternative is chosen from the choice set by an individual. The utility of the alternatives calculates the choice probabilities. This research searches for the probability that the sustainable hydrogen grid with a lower level in reliability and cost is chosen over the current natural gas grid. An assumption needs to be made about the probability distribution of the random utility ε to determine the choice probability and utility [17][22]. In this research two models are used to estimate the utility, the multinominal logit (MNL) model, and the mixed logit (ML) model.

MNL model

The MNL model is the most widely used and is mainly popular due to the simplicity. However, the model makes strong assumptions about the behavior of individuals. The most notable assumption is the Independence of Irrelevant Alternatives (IIA) property. The IIA property assumes that by adding a new alternative to the choice set, the choice probabilities of all other alternatives fall proportionally [22][23][24]. Furthermore, in MNL models the ε term of all the alternatives is drawn independently from a distribution with the same variance. This is known as the i.i.d. error term assumption [25]. The IIA property is seen as the main drawback of the MNL, but it also causes that the model is simple to estimate since the formula of the choice probabilities is closed form [18]. The linear additive utility function of the total utility of the specific alternative is as follows [18]: $Uin = Vi + \varepsilon in$

"Uin" displays N's utility of alternative i, "Vi" is the systematic utility of alternative i, "εin" displays the random utility (error term) of alternative i by individual n. The systematic utility is typically modeled as a linear function with the following form: $Vi = ASCHydrogen + \sum \beta m * xim$. Where "$\beta m$" displays the weight of the parameter of attribute m and "xim" shows the attribute level of attribute m of alternative i. The utility function based on the choices made by the respondents can be added with interaction effects that influence the choice of a system or the WTP for reliability.

ML Model

Due to similarities between alternatives, nesting effects arise. The MNL model assumes there are no correlations between the unobserved utilities (ε) of the alternatives with similar attributes (i.i.d. error term assumption). By wrongly assume that the i.i.d. error term assumption holds, creates biased parameter estimates. An ML model adds another error component to the utility function that captures the common factors between alternatives [18][24]. The error component displays the utility of the unobserved factors of the hydrogen alternatives.

Secondly, a Mixed Logit model captures taste heterogeneity by letting the parameters β vary across individuals. The MNL model wrongly assumes that the β's are fixed and that the taste does not vary across individuals. Furthermore, it is realistic that choices made by the same individual are correlated, since their preference and taste influence their choice. By assuming that these choices are uncorrelated creates underestimated standard errors of the parameters. ML models solve this problem by capturing panel effects. The panel is the complete sequence of the choices made by one individual [18][24].

It is expected that the attitude towards hydrogen and sustainable heating will influence the choice for an alternative hydrogen design or the WTP for reliability. Moreover, the incorporation of attitudes is of additional value for Stedin. Therefore, this research estimates a hybrid choice model by adding a latent variable model to the discrete choice model. This makes it possible to use attitudes as explanatory variables in the choice model.

By applying an explanatory factor analysis (EFA) on the statements, the latent factors can be identified and included in the hybrid model [26]. It is essential to be aware of the criticism of hybrid choice models. A first criticism on the incorporation of attitudes is that specific attitudes have a strong correlation with behavior. A causal relation causes this correlation. Specific attitudes will affect behavior, but specific attitudes are also influenced by behavior. The reverse causality is ignored in hybrid models. More research is needed to understand the bidirectional relation between attitude and choice behavior [27]. Another problem identified is that attitudes and perceptions are measured at one point in time [28]. This causes that the latent variables only observe differences between individuals. They do not observe the variation within or the changes for the same individual. There is no causal inference at the level of an individual.

Consequently, hybrid models do not support the use of policies that aims to change the attitude (latent variable) to change choice behavior [27][28]. This research chooses to incorporate the attitudes in the model estimation, caused by the expected additional value for Stedin and the increase in the explanatory power of the model. No policy recommendations must be given about influencing the attitudes to change the preferences of the households. Finally, to give insights into the mean preference for a hydrogen system with a lower level of reliability, a model is estimated without the attitudes.

4. Results

The ML model is used to analyze the results instead of the MNL model to minimize the chance of bias estimates. The estimates of the sigmas for capturing the taste and the preference heterogeneity do not equal zero, and the estimates of these sigmas are significant. Furthermore, by comparing the model fit of the two models based on the likelihood ratio test and the Rho Squared, it can be concluded that the combined ML model fits the data better than the MNL model. This implies using the ML model instead of the MNL model.

Estimates

On average, Dutch households prefer the design of a hydrogen system with a lower level of reliability over the current natural gas system. However, for the preference of an alternative hydrogen design over the current system, there is a significant level of unobserved heterogeneity that cannot be explained by the variables added to the model.

The maximum indoor temperature mostly influences the choice of an alternative hydrogen system. Also, cost reduction has a great influence on the choice of an alternative design of the hydrogen system. The time constraint least influenced the choice for an alternative hydrogen design. This attribute is valued negatively, and there is a general dislike for a more extended period with constraints.

Finally, households have a general dislike when only one room is allowed to be heated. The attribute “amount of rooms” influenced the choice of a system the most after the indoor temperature and cost reduction.

Households are heterogeneous about the utility they obtain from different levels of the maximum indoor temperature, the number of rooms heated, and the cost reduction. This research found no significant heterogeneity for the time constraint attribute. There is consensus about the dislike for the amount of time with a constraint.

Willingness To Pay (WTP)

This report identifies a gap between the average WTP for reliability and the current cost of the natural gas system. The identified gap holds on a 95%-confidence interval, which means that this research can conclude the gap with 95% certainty. The expectation is that a hydrogen system will be more expensive than the current natural gas system, especially in the beginning and during the transition phase. In the beginning, there are no infrastructure or generation facilities. The implementation of expensive hydrogen infrastructures on a local level will significantly increase the cost.

The construction of an electrolyser serving demand until -7℃ instead of -12℃ can decrease the cost by 15%. The cost reduction caused by lowering the investment costs can decrease the gap between the WTP and the cost of heating. Cost reductions of 15% ensure that the gap between the WTP and the cost cannot be concluded on a 95% confidence interval.

If the current regulation forces the grid operators and energy companies to implement a hydrogen system that meets the current reliability regulation, the gap between the WTP of households and the cost of heating will further increase instead of decrease.

Households' expectation of using sustainable heating significantly influences the WTP for reliability. Households that expects to use sustainable heating are willing to disconnect their house from the natural gas grid and use sustainable heating as an alternative. The gap between the WTP and the cost will further increase when the household has a higher expectation of using sustainable heating. Grid operators cannot force households to change their heating connections from natural gas to sustainable fuels. Furthermore, one can expect that always a certain percentage of inhabitants should be willing to change their heating connection before the transition can take off.

Therefore, the first neighbourhoods that shift from natural gas to hydrogen are willing to use sustainable heating. The transition phase is expensive, especially if the system should be very reliable from day one. The results imply that households willing to use sustainable heating prefer to reduce the reliability of the hydrogen system to ensure the system will not become too expensive. Therefore, it is crucial to consider making reliability regulations for the beginning and transition phase less strictly than the final regulations. The transition regulations can help the development of an affordable, reliable, and sustainable hydrogen grid.

5. Discussion

The main scientific contribution of this research is the assessment of the trade-off between the reliability and affordability of an energy system from the households' perspective. The analysis of this particular trade-off has never been the subject of discussion. The system used for heating has reliability regulations. Based on these reliability regulations, the cost of the energy infrastructure is determined. The reliability has never been weighted to the affordability goal, especially not from the households' perspective. This research provides insights into the preferences of the households in the trade-off between a reliable and affordable energy system. Moreover, this research quantifies the households' Willingness To Pay (WTP) for energy systems.

A higher level of reliability increases the cost (CPB, 2014; Brown, et al., 1997). The total cost line in Figure 2 shows this relation. This research shows that investments in the natural gas system are not economically efficient—the cost of reliability outreach the average WTP for reliability by the Dutch households. Households do not transfer the efforts taken to create a very reliable natural gas grid into benefits. The natural gas grid has no optimum between reliability and cost since the cost does not display the benefit. The relationship between the cost and reliability of the natural gas system is in the upper right part, stiped in blue in Figure M.1. The cost and level of reliability are higher than the optimum shown by the green line.

Implementing a hydrogen system will be more expensive than the current cost of the natural gas infrastructure. Especially the cost of reliability will increase. Therefore, the cost and reliability need to decrease to create an economically efficient hydrogen system. If the current reliability regulations are guaranteed, this research expects that the relationship between cost and reliability in a hydrogen system will be visualized by the orange striped square in Figure M.1. The level of reliability must be reduced to create an optimum between the cost and reliability.

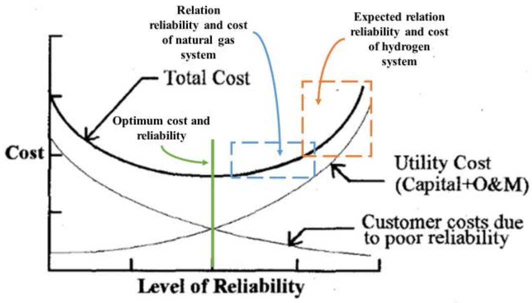

Figure M.1 - [Reliability Cost Curves natural gas system and hydrogen system]. Retrieved from: Brown, et al., 1997. [Online Image]

Also, several limitations of this research can be identified. The first shortcoming of this research is that no representative sample for the Dutch population filled in the survey. It is expected that because the sample is unrepresentative, the use of another sample might lead to different outcomes. Furthermore, it can be that self-selection has occurred. Respondents were free to fill in the survey, which can imply that respondents with an opinion about the subject are more likely to fill in the survey.

Another bias that is likely to occur in choice experiments is the hypothetical bias. The researcher is never sure whether the choices made in the survey are the same as in real life. There are no real consequences to the choices.

Furthermore, there is a significant amount of unobserved heterogeneity. The unobserved heterogeneity implies that the attributes do not explain all the factors that households make when choosing a system used for heating. Households likely consider more attributes when deciding for a system used for heating than added in the stated choice experiment. Another limitation of this research is the presence of non-trading behavior. The drivers of non-traders differ, but almost impossible to recognize the drivers based on the data. Non-trading behavior can influence the parameter estimates and the WTP estimates.

Lastly, the period of the conduction of the research should be considered. The survey is distributed in summer, and it is reasonable to assume that respondents are more optimistic about reducing their gas use compared to winter. Furthermore, it is essential to consider that due to the COVID-19 crisis, households are more often at home. Households will experience the downsides of a less reliable system more than when they are away from home more often, which may lead to too negative estimations of parameters.

6. Conclusion

Concludingly, the government should reconsider the national reliability regulations and look into creating regional reliability regulations for the transition phase. The system does not be as reliable as it is today. For the transition phase, it is crucial to look at conditions on a local level. In the coming years, local conditions should be used to determine the trade-off between reliability and affordability. Also, the hydrogen system does not have to be very reliable from day one. Transition regulations can help to start the hydrogen transition affordably.

Not only the generation capacity should be used to match supply and demand. Households can reduce their hydrogen demand during peak hours. Grid operators can incentivize households to reduce their demand, or technical constraints can be added to the system to make sure households do not use not too much hydrogen during peak hours. Moreover, advanced conversion systems to spread the demand can be implemented in houses. Finally, grid operators can restrict large consumers in their hydrogen demand. The hydrogen needs to become more affordable and less reliable from the perspective of the households. Grid operators, energy companies, and the government should guarantee reliability in another way they do today.

7. Recommendations

Stedin should start collaborating with other grid operators and perhaps energy companies and lobby for different reliability regulations. The government should ease the national reliability regulations, for example, to -7°C to create an affordable and reliable system desired by households. Furthermore, the grid operators should lobby for creating transition regulations that focus on the regional character of the transition and the fact that the first neighbourhoods are frontrunners in the hydrogen system. Stedin should support the lobby by identifying different options to match supply and demand during shortages. They need to collaborate with energy companies and monitor the available supply of hydrogen.

Moreover, grid operators should consider the different options to ensure that they can lower demand during shortages. They need to identify large energy consumers and inventory their willingness to reduce their demand during shortages. Also, they should consider ways to incentivize households to reduce their demand and whether it is legally possible to create contracts for end-users.

Further research must reveal the possibility of implementing technical constraints in the gas grid to reduce hydrogen distributed to houses. Also, the effect of advanced hydrogen conversion systems on the spreading of peak demand must be investigated. Furthermore, research must determine to what extent the wishes of the households can be taken into account for the design of a future proof hydrogen system. The design must be stable and not much influenced by the changing perceptions of households. Qualitative research can provide insights into ways to incorporate flexible demand and the preferences of households in the hydrogen design.

Moreover, qualitative research is necessary to determine what aspects of energy systems the households find essential.

The influence of generating more hydrogen on the capacity of sustainable electricity sources is left out of scope. One can expect that when more hydrogen capacity must be available, more electricity capacity is needed—this leads to an even more expensive infrastructure. More research should reveal the exact influence. Finally, this research focusses on the incorporation of the preferences of households on the design of a hydrogen grid. Further research should indicate whether the same relations can be found in other heating sources, as electricity and heating grids.

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