Waterstof in de gebouwde omgeving

Technologische en economische haalbaarheid van waterstof in de gebouwde omgeving | Babette Korevaar

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DWa

HYDROGEN FOR HEAT SUPPLY IN THE DUTCH BUILT ENVIRONMENT

Internship report – master Energy Science

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Abstract

The Netherlands wants to have a decarbonised built environment by 2050. However, it is still questionable how this goal is going to be reached. DWA, a consultancy and engineering firm, is working actively on this issue by advising their clients with smart and sustainable solutions for buildings and areas. Currently, hydrogen is seen as a major breakthrough in renewable energy. The question that remains for DWA is how they should interpret the developments of hydrogen in making the existing residential areas free of natural gas. This study examines (I) the feasibility to substitute the current natural gas use of the built environment by Dutch green hydrogen and the (II) expected costs for a hydrogen heating system by determining the Total Cost of Ownership for different price scenarios. Key findings of the performed analyses are; if it is intended to use renewable electricity produced in the Netherlands, the deployment of hydrogen in the heat supply of the Dutch built environment is not a realistic step by now. This because the plans for sustainable electricity generation do not allow these quantities of hydrogen production. In addition, deployment of a hydrogen heating system is not the most cost effective natural gas-free alternative. A numerous of price scenarios are proposed to indicate for which hydrogen supply price a hydrogen heating system is competitive with natural gas-free alternatives. Dutch green hydrogen production costs should drop to a level that is not feasible by the next 10 to 15 years.

Keywords: decarbonisation, built environment, hydrogen, TCO, hydrogen heating systems, renewable electricity, Dutch green hydrogen production

Management samenvatting - NL

De Nederlandse overheid heeft als doel om in 2050 de CO_2 uitstoot te verminderen met 80 - 95 % procent ten opzichte van 1990. Dit heeft voor de gebouwde omgeving als gevolg dat aardgas niet langer meer zal worden gebruikt voor de elektriciteit- en warmteproductie. Echter, de transitie naar aardgasloos is een moeilijke opgave met veel uitdagingen op technologisch, organisatorisch, sociaal, financieel en praktisch level, wat maakt dat het nog onzeker is hoe het duurzame energiesysteem van de toekomst er zal uitzien. Momenteel wordt waterstof gezien als een belangrijke doorbraak voor de energietransitie en wordt hierdoor veel besproken in de media. Deze zogenaamde "waterstof hype" beinvloedt de publieke opinie, wat het beeld schetst dat waterstof hét alternatief is van aardgas voor in de gebouwde omgeving. Een groot voordeel van waterstof is dat het voor veel doeleinden inzetbaar is, waardoor het in veel sectoren kan worden gebruikt als duurzaam alternatief. Het potentieel van waterstof is bekend, maar heden ten dage is er nog weinig bekend over hoe de energiedrager zich verhoudt tot andere aardgasvrije alternatieven, zowel op technologisch als economisch gebied. Daarnaast is er ook nog geen zekerheid over de hoeveelheid waterstof die er in de toekomst beschikbaar is, wat de inzet van waterstof voor de warmteproductie in de gebouwde omgeving een belangrijk maar complex vraagstuk maakt voor DWA. De vraag die voor DWA rest is hoe ze de ontwikkelingen van waterstof moeten interpreteren om de bestaande woongebieden aardgasvrij te maken.

Om de rol van waterstof te bepalen in de warmtevoorziening van de gebouwde omgeving is er in dit rapport onderzoek gedaan naar de technologische en economische haalbaarheid van waterstof. Er is onderzocht hoeveelheid waterstof er geproduceerd moet worden om het aardgas gebruik in de gebouwde omgeving te vervangen. Daarnaast is de economische haalbaarheid van een waterstof warmtesysteem getest met gebruik van de Total Cost of Ownership (TCO). De verkregen uitkomsten kunnen worden vergeleken met de TCO van alternatieve aardgasvrije warmte systemen.

Bij het bepalen van de hoeveelheid beschikbare waterstof voor de gebouwde omgeving moet er rekening gehouden worden met de afname van waterstof door andere sectoren en de hoeveelheid beschikbare duurzame elektriciteit in Nederland. Er is aangenomen dat de sectoren die momenteel gebruik maken van grijze waterstof voorrang zullen hebben op de gebouwde omgeving in de afname van groene waterstof. Deze aanname is gebaseerd op het feit dat de gebouwde omgeving meerdere alternatieven heeft voor een duurzame warmtevoorziening, waar de sectoren die waterstof gebruiken als eindproduct dit niet hebben. Momenteel gebruikt enkel de chemische industrie grote hoeveelheden waterstof (163 PJ per jaar). De gebouwde omgeving daarentegen gebruikt per jaar 408 PJ aardgas voor warmteproductie. In de figuur hieronder is te zien hoe groot het gebied is dat aan zonnepanelen moet worden gericht om de chemische industrie (paars) en de gebouwde omgeving (rood) te voorzien van waterstof (Figuur 1). Indien als primaire energie windenergie wordt gebruikt in plaats van zonnenenergie zal er 270% van de total geinstalleerde capaciteit aan wind

turbines in 2030 gebruikt moeten worden voor waterstof productie, waarvan 75% zal worden verbruikt voor de chemische industrie en 195% voor de gebouwde omgeving.
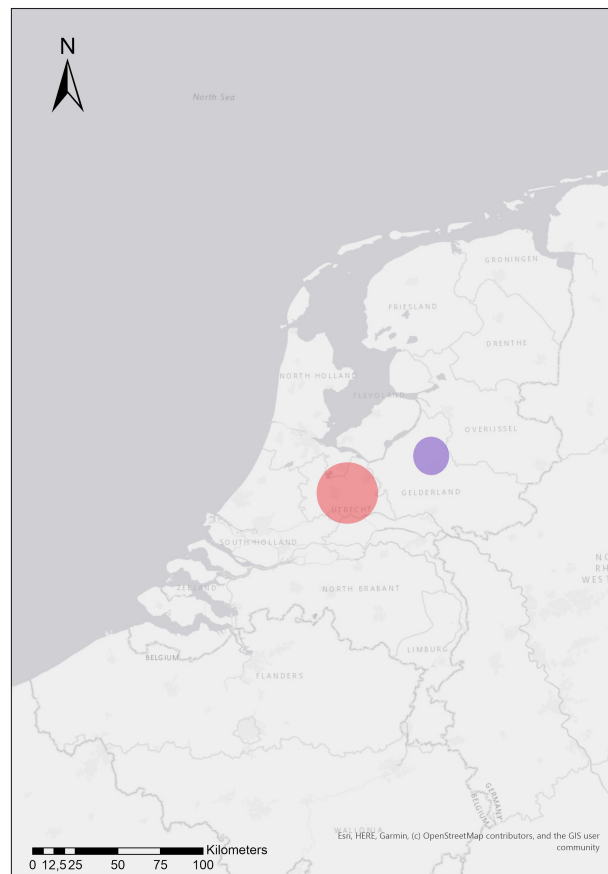

Figure 1: Kaart van Nederland, waar de paarse stip het gebied weergeeft dat nodig is voor de installatie van zonnepanelen om 163 PJ groene waterstof aan de chemische industrie te leveren en de rode stip het gebied dat nodig is om 408 PJ waterstof aan de gebouwde omgeving te leveren. Aangenomen wordt dat de jaarlijkse productie van de zonnepanelen 150 kWh/m^2 is.

De economische analyse is uitgevoerd voor 3 verschillende prijsscenarios, namelijk: (A) Waterstof geproduceerd in Nederland in 2020, (B) Waterstof geproduceerd in Nederland in 2030 en (C) Waterstof geproduceerd in de Sahara in 2020. Per scenario zijn 2 cases uitgevoerd: case (I) waterstofverwarmingssysteem in de huidige status van het gebouw en case (II) een waterstofverwarmingssysteem in combinatie met isolatie. In scenario A is er uitgegaan van een waterstof productieprijs van 0.1460 €/kWh (4.87 €/kg), scenario B van 0.0876 €/kWh (2,92 €/kg) en scenario C 0.0300 €/kWh (1.00 €/kg). Deze prijs is exclusief belastingen, netwerkkosten en marge. Voor de analyse is er vanuit gegaan dat de kosten voor belastingen en het variabele deel van de leveringskosten gelijk zijn aan die van aardgas (gestandardiseerd aan energie-inhoud), waarbij een percentage marge van 20% is berekend op de productieprijs van waterstof. De gehanteerde kostenposten voor de TCO zijn weergegeven in Appendix B. De belangrijkste resultaten die naar voren kwamen in de economische analyse worden hier verder toegelicht. In figuur 2 en 3 is de kostenopbouw van de TCOs in scenario A voor case I en case II te zien. In scenario A wordt er vanuit gegaan dat de huishoudens per 2020 een omschakeling zullen maken naar waterstof. De gemiddelde TCO van scenario A in case I is € 88,075

en voor case II is € 59,698. In beide gevallen zijn de TCO's hoger dan alternatieve gasvrije opties, wat aangeeft dat een waterstofverwarmingssysteem tegen 2020 geen kosteneffectieve optie is. Het gemiddelde van de TCOs van case II is echter in alle uitgevoerde scenario's lager dan in case I, wat aangeeft dat zelfs in een scenario met lage prijzen voor waterstof, de isolatiekosten in de meeste geanalyseerde woningen kunnen worden terugbetaald.
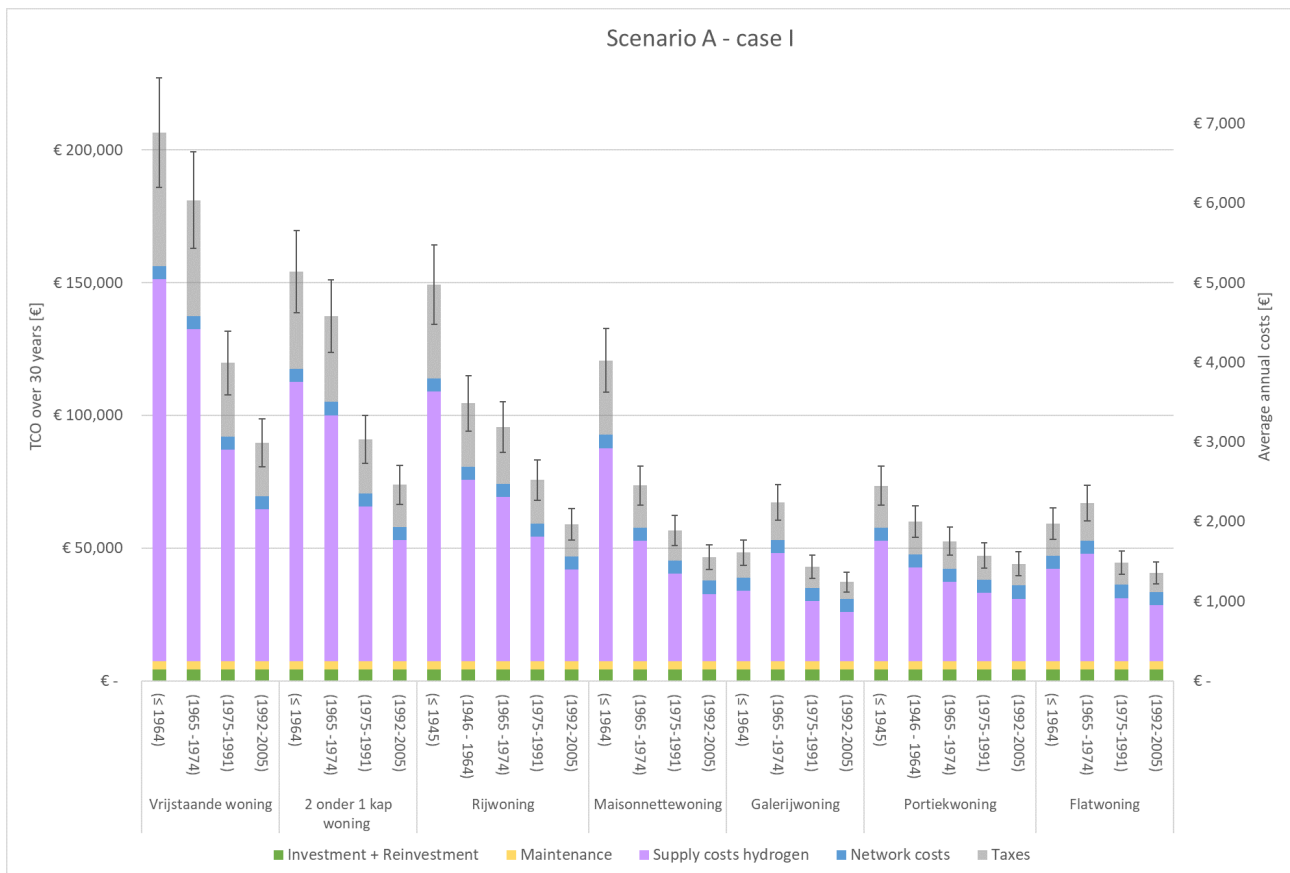

Figure 2: TCO over 30 jaar en de gemiddelde jaarlijkse kosten voor case I van scenario A weergegeven per gebouw. De kosten zijn onderverdeeld in vier kostencomponenten, namelijk: (I) investeringen en herinvestering, (II) energiekosten bestaande uit leveringskosten en netwerkkosten, (III) onderhoudskosten en (IV) belastingen. Als er geen belastingen worden geheven op waterstof, kan de laatste kostencomponent worden uitgesloten. De foutbalken geven een foutmarge weer van 10%.

De inzet van een waterstofverwarmingssysteem is het meest voor de hand liggend in gebouwen waar isolatiekosten niet worden terugverdiend door het voordeel van de energiebesparing. Voor alle 3 scenario's geldt dit voor 'gallerijwoning' en 'flatwoning' met een bouwjaar tussen 1991-2005, aangezien case II een hogere TCO had dan case I in deze bebouwing. Daarnaast kwamen de volgende bevindingen naar voren in scenario B en C. De gemiddelde TCO van scenario B is bijna concurrerend met alternatieve aardgasvrije opties, wat erop wijst dat een waterstofprijs van 0.0876 €/kWh (2,92 €/kg) dichtbij het omslagpunt ligt. Scenario C lijkt de betaalbare optie, maar of waterstof ooit voor deze kostprijs beschikbaar komt in Nederland, is nog maar de vraag.
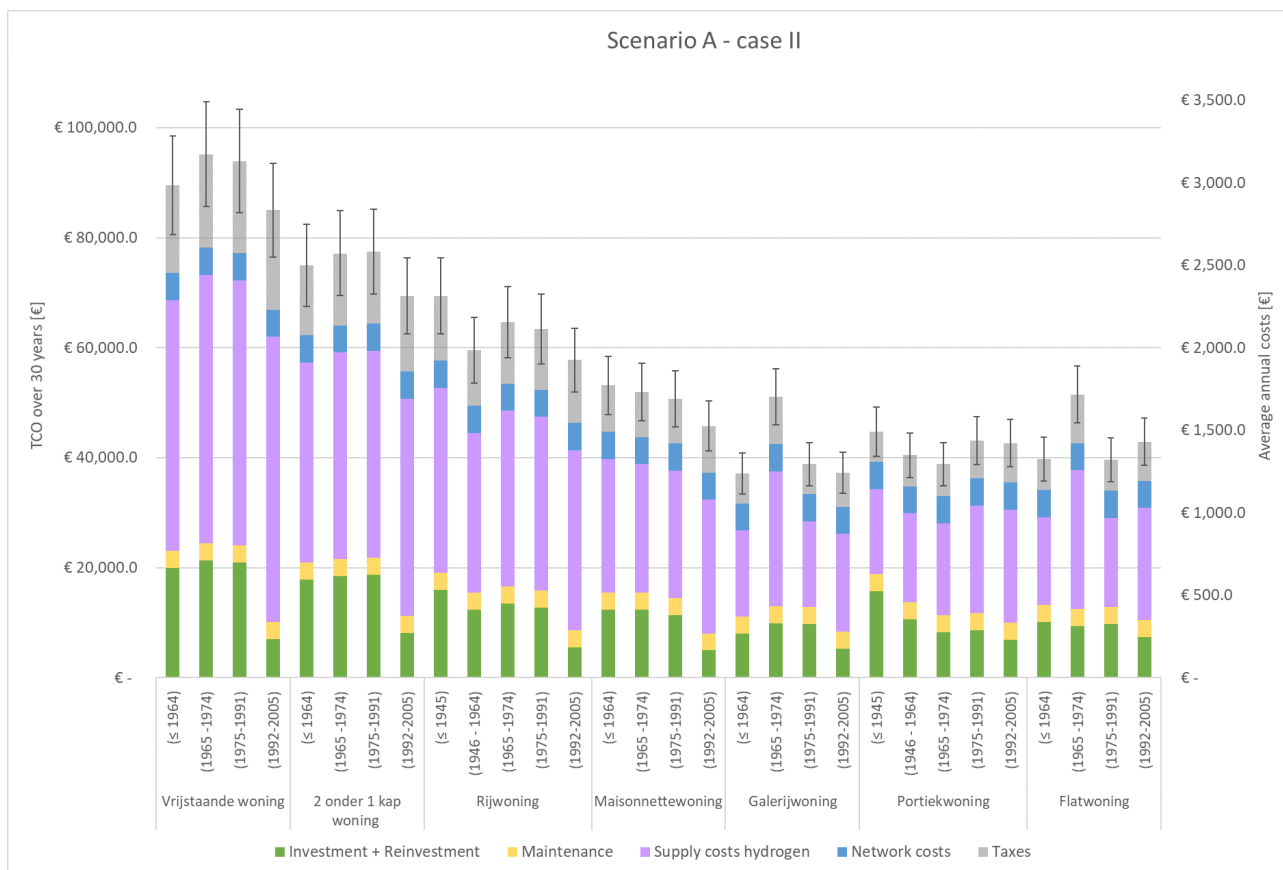
Figure 3: TCO over 30 jaar en de gemiddelde jaarlijkse kosten voor case II van scenario A weergegeven per gebouw. De kosten zijn onderverdeeld in vier kostencomponenten, namelijk: (I) investeringen en herinvestering, (II) energiekosten bestaande uit leveringskosten en netwerkkosten, (III) onderhoudskosten en (IV) belastingen. Als er geen belastingen worden geheven op waterstof, kan de laatste kostencomponent worden uitgesloten. De foutbalken geven een foutmarge weer van 10%.

Over het algemeen kan worden gesteld dat de rol van waterstof in de warmtevoorziening van de gebouwde omgeving de komende tien jaar zeker klein zal zijn. Dit omdat er onvoldoende hernieuwbare elektriciteit beschikbaar is voor de productie van groene waterstof en de kosten heden ten dage veel te hoog zijn om te kunnen concurreren met alternatieve gasvrije opties. Niettemin, als de waterstofproductieprijs onder de 2,92 €/kg zakt, kan dit veranderen. De prijsontwikkeling van waterstofproductie is dus alles bepalend voor de inzet van waterstof in de gebouwde omgeving. Echter, zoals eerder vermeld is er een tekort aan duurzame elektriciteit om de waterstof groen op te kunnen wekken in Nederland. Met betrekking tot het overheidsbeleid beveelt deze studie aan om rekening te houden met de beschikbare hoeveelheid hernieuwbare elektriciteit bij het verlenen van financiële steun voor projecten die zich focussen op waterstofproductie. De productie van waterstof heeft relatief hoge rendementsverliezen, die in het geval van grijs elektriciteitsgebruik resulteren in het vergroten van de CO_2-uitstoot. Indien Nederland onafhankelijk wilt zijn in haar energievoorziening zullen de plannen voor duurzame elektriciteit moeten worden opgeschaald. De huidige ontwikkelingsplannen zijn een stap in de goede richting, maar bij lange na niet voldoende en zeker niet als er ook nog elektriciteit ingezet zal moeten worden voor waterstofproductie voor de gebouwde omgeving.

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Nomenclature

α Index rate [-]

η Efficiency [%]

ϕ Fraction of annual [yr^{-1}]

CAPEX   Capital expenditures [€]

E   Energy [MWh]

OPEX   Operating expenditures [€/year]

Q   Heat [MWh]

TCO   Total Cost of Ownership [€]

Chapter 1

Introduction

The climate ambition of the Dutch government is to achieve a CO_2 emission reduction of 95% by 2050 compared to the levels of 1990 [1]. Therefore, it is intended that natural gas will no longer be used for electricity and heat supply in buildings by then. However, this transition to a gas-free built environment is a difficult task with many challenges on a technical, organisational, social, practical and financial level [2]. The lack of certainty on these levels causes that it is yet unclear how this goal can be achieved. DWA, a consultancy and engineering firm, is working actively on this issue by advising their municipalities, public housing, corporations etc. with smart and sustainable solutions for buildings and areas. Their mission is: 'We make sustainability work'. They bring parties together and act as director in the complex spectrum of policy, technical, financial, organisational and legal elements, with the aim of achieving an integrated sustainable energy supply system.

Currently, hydrogen is seen as a major breakthrough in renewable energy and is hotly debated in the media. 'New solar panels produce direct green hydrogen' [3], 'Shell and Gasunie are investing in Europe's largest hydrogen project' [4], 'The world can count on hydrogen' [5] and 'Hoogeveen builds the first hydrogen district in the Netherlands' [6] are topics the population is confronted with on a daily basis. Some initiatives even seem to target the Sahara for hydrogen production for the Netherlands [7]. This so-called 'hydrogen hype' in media is highly influential on the public opinion, which generates the impression that hydrogen is the solution for the energy transition. Even government agencies are influenced by this hype, making this energy carrier a subject of a huge amount of lobbying for the energy transition [6]. However, it is still uncertain how the developments of hydrogen should be interpret in making the existing residential areas free of natural gas.

A main advantage of hydrogen is that it can be deployed for many purposes. Therefore, hydrogen can play an important role in the energy transition, as it can be used as fuel, storage and feed stock [8][9]. For example, hydrogen (I) makes it possible to apply large-scale integration and generation of sustainable electricity, (II) is an energy carrier that can be distributed across sectors and regions (III) can act as a buffer in energy systems, (IV) can be used to decarbonise the transport sector, (V) industrial energy use (VI) and building heat and power, and (VII) can provide a clean feed stock for industry [10][8]. Here, point six can be interesting for DWA. Its wide spectrum of applications creates many opportunities, but also may cause for competition between sectors case of scarcity. In this case, with sectors there is referred to the five sectors of the Dutch climate agreement namely: industry, electricity, agriculture, transport and

the built environment. These sectors experience the same issues regarding decarbonisation. It is important to embrace new sustainable technologies in this uncertain transition period as there are still insufficient sustainable alternatives available as substitute for natural gas until today. The potential of hydrogen is known, but there is little transparency in how it relates to existing resources, as well from a technological as an economic perspective. Moreover, there is still no certainty on the quantities of hydrogen that will be available in the future yet. Making the deployment of hydrogen for heat production in buildings an emerging but complex subject to DWA.

To gain better understanding of this energy carrier and how it can contribute to decarbonise the built environment sector, the following has to be taken into consideration. Hydrogen is the smallest and most common element on earth. Its energy content per cubic meter is at equal pressure approximately three times as small as that of natural gas [11]. At standard pressure and temperature the energy content of hydrogen is 10.8 MJ/Nm^3, where that of natural gas is 36 MJ/Nm^3 [12]. However, its energy density per kilogram is 120 MJ/kg, which is far higher than natural gas, which is 50 MJ/kg. By increasing pressure or decreasing temperature the energy content per cubic meter of hydrogen can be increased [13]. Furthermore, hydrogen is an odorless and colorless gas which makes the deployment of hydrogen more complex in terms of safety. The fact that it is the smallest molecule on earth makes adding an odorant or colour (which makes it easier to detect) a complicated issue, because the odorant is a larger molecule than hydrogen. Another important point to consider is the origin of hydrogen. Based on the production, hydrogen can be divided into three categories; *grey*, *blue* and *green* hydrogen. However, the physical and chemical properties do not change due to the method of production. In this case, 'grey' and 'blue' hydrogen are produced by fossil fuels. Here, blue is produced with carbon capture, where grey is produced without. 'Green' hydrogen is produced in the most sustainable way, since water is split into hydrogen and oxygen by use of renewable electricity (e.g. wind turbines or solar panels), which means no CO_2 is emitted. However, this way of production depends on the availability of sustainable electricity. Since the aim is to have a CO_2 neutral built environment by 2050, production of 'grey' or 'blue' hydrogen is not seen as a solution to achieve this target.

The idea of a 'hydrogen economy' is definitely not new [14]. A lot of research has been done on this matter, however the application of hydrogen in the built environment is still in its infancy. Even though there has been severe criticism about the suitability of hydrogen for the built environment, the current opportunistic view in the media gives many people the idea that they can rely on the rise of hydrogen. This demotivates people to take initiatives themselves in the field of energy saving or applying energy efficient technologies [15][16][17]. It is certain that hydrogen will contribute to the energy transition, but when and how is unclear yet. To make efficient use of this currently scarce energy carrier, it is important that it is used by sectors that are most in need of it. However, the question that remains today is; will this be the built environment?

1.1 Research questions

To get a better understanding of the problem stated above, the following research question is proposed.

What could be the role of hydrogen in the heat supply of the Dutch built environment?

The research question is answered by use of two sub questions. For each sub-question a brief explanation is

given below.

I To what extent is it feasible to substitute the current natural gas use of the built environment by Dutch green hydrogen?

This part examines how much hydrogen the Netherlands should produce if the gas-users of the built environment would wait for the rise of hydrogen. This by use of Dutch green hydrogen, which is in the Netherlands produced using Dutch renewable electricity. Furthermore, it analyses the surface or landscape needed for wind and solar technologies to produce the quantities of hydrogen needed. Besides, the current hydrogen demand by other sectors should also be sustainable in the near future. Taking this into consideration there is determined if there is still hydrogen left for the built environment.

II What are the expected costs of a hydrogen heating system in the Dutch built environment?

In case there is hydrogen available for the built environment, this question considers the costs of a hydrogen heating system for different types of buildings in the Dutch built environment. By performing an economic assessment for 30 buildings, which together reflect the total Dutch housing stock a conclusion can be drawn about the affordability of such a system. The economic indicator that is used to perform this economic assessment is the Total Cost of Ownership.

The remainder of this proposal is structured as follows. Firstly, the theoretical background is explained, which elaborates on hydrogen as energy source and gives an overview of the existing technologies. In the subsequent chapter, the methodological approach in order to answer the research question is appointed. The methodology is explained based on two concepts which are related to the proposed sub-questions. After the methodology, the results are presented based on the two concepts. Results A discusses the available green hydrogen for the built environment, where Results B contains an economic assessment where the costs for a hydrogen heating system is calculated per different type of building. The results are discussed in the discussion section, where recommendations and follow-up research are noted. Lastly, the conclusion provides an answer to the main- and sub-questions in this study.

Chapter 2

Theoretical background

To analyse hydrogen as energy carrier for the built environment, the *hydrogen energy chain* has to be determined. This system refers to the *production*, *transportation*, *storage*, *conversion* and *end usage* of hydrogen [18]. The next section discusses the technologies related to the processes within the hydrogen energy chain. The analysed system needs to be in operation before 2050, meaning that the technologies need to become commercially available within the foreseeable future. An overview of the technological and economic parameters per technology are presented in Appendix A.3.

2.1 Production

Electrolysis is an electrochemical process where water is split into hydrogen and oxygen by use of electricity [19]. The overall reaction with the thermodynamic energy values is described in Equation 2.1 [20]. Electrical and thermal energy is needed to initiate the process, which means it is endothermic.

$$H_2O_{(l)} + 237.2 \text{ kJ mol}^{-1}(\text{electricity}) + 48.6 \text{ kJ mol}^{-1}(\text{heat}) \rightarrow H_2 + 1/2O_2 \tag{2.1}$$
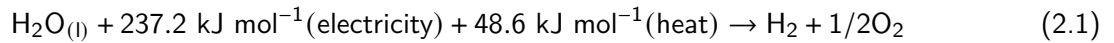
Technologies that use the electrolysis principle produce green hydrogen if the electricity is renewable. Figure 2.1 shows a simplified concept of three different electrolyser technologies [21]. A brief explanation of electrolyser technologies that can produce green hydrogen is given below.
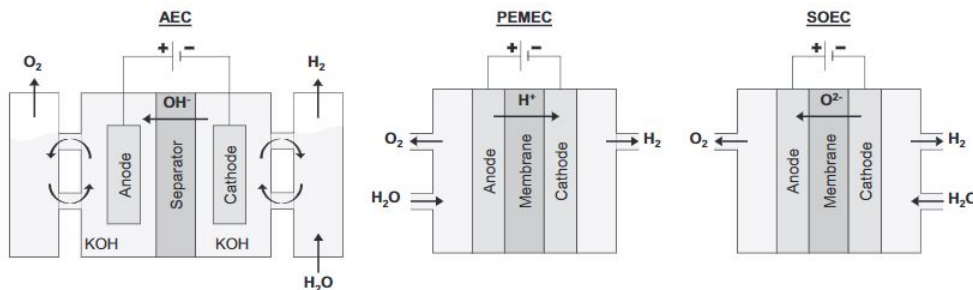
Figure 2.1: Simplified concept of the three different electrolyser technologies to produce green hydrogen. AEC is an Alkaline Electrolyser Cell, PEMEC is a Proton Exchange Membrane Electrolyser Cell and SOEC is a Solid Oxide Electrolysis Cell.

Alkaline Electrolyser Cell

A mature technology is the Alkaline Electrolyser Cell (AEC) [22]. This electrolyser has been commercially available since the 1920s, is mostly used for large-scale industrial processes and their lifetime can reach up to 15 years [21]. Based on the materials used for the electrodes and the temperature and pressure conditions, the efficiency of an AEC can vary between 46% and 82%. The chemical reaction process in the AEC is visualised in Equation 2.2 and 2.3 [22]. Usually potassium hydroxide is used as solid electrolyte (KOH in Figure 2.1, AEC) [23].

$$2H_2O(l) + 2e^- \rightarrow H_2(g) + 2OH^-(aq) \tag{2.2}$$

$$2OH^-(aq) \rightarrow \frac{1}{2}O_2(g) + 2e^- \tag{2.3}$$
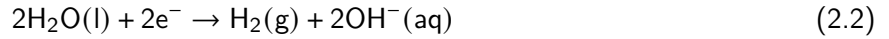
As can be derived from the chemical equations 2.2 and 2.3, hydrogen and oxygen leave the AEC in gas phase. The pressure of this gas is ranging between 1 to 30 bar depending on the pressure conditions during this process. The purity level of the produced hydrogen varies between 99,7% and 99,9% [23].

Proton Exchange Membrane Electrolyser Cell

Proton Exchange Membrane Electrolyser Cells (PEMECs) are less mature than AECs and mostly used in small-scale applications [21]. The polymere membrane that is used, allows that only hydrogen can pass through [23]. This technology is due to its high power density, high cell efficiency, flexible operation and its highly compressed and 99.99% pure hydrogen output more advantageous than AECs [22]. The operating pressure can reach up to 200 bar, which is corresponding with the pressure required for storage. However, this technology has on average a shorter lifetime, lower operating temperature ($< 80°C$) and is more expensive than an AECs. In Equation 2.4 and 2.5 the chemical reactions that occur in the PEMEC are presented. Currently, the efficiency of a PEMEC is between 73% and 86% depending on the system load [23].

$$H_2O(l) \rightarrow \frac{1}{2}O_2(g) + 2H^+(aq) + 2e^- \tag{2.4}$$

$$2H^+(aq) + 2e^- \rightarrow H_2(g) \tag{2.5}$$
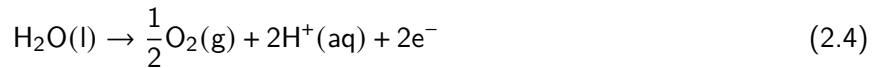
Solid Oxide Electrolysis Cell

Currently, Solid Oxide Electrolysis Cells (SOECs) are using solid ion-conducting ceramics as electrolyte and are in a pre-commercial phase. A main advantage of this technology is that hydrogen is produced at very high temperature. This ensures that the latent heat has not to be provided due to vaporisation by electricity, which causes that considerably higher operating efficiencies can be achieved [21][23]. Equation 2.6 and 2.7 shows the chemical reactions that take place in a SOECs [22]. Hydrogen purity can reach up to 99.9% using this technology.

$$H_2O(g) + 2e^- \rightarrow H_2(g) + O^{2-} \tag{2.6}$$

$$O^{2-} \rightarrow \frac{1}{2}O_2(g) + 2e^- \tag{2.7}$$

2.2   Storage

As mentioned, the energy density of hydrogen is relatively low at standard temperature and pressure compared to fossil fuels. Therefore it has to be stored under high pressure or low temperature to increase energy density. These requirements ensure that storage options are limited. Nonetheless, hydrogen storage technologies provide a good opportunity to store seasonal energy. The two most common options for hydrogen storage are discussed below.

Hydrogen tanks

Hydrogen can be stored in high pressure tanks, which is currently the most common way to store hydrogen. The pressures range between 200 and 350 bar to increase the energy density. Storage costs for hydrogen tanks will be around 7.69 €/MWh [24]. Nonetheless, this storage option is not suitable for large scale, as even under high pressure the energy density of hydrogen is still relatively low [13].

Salt caverns

Hydrogen underground storage in salt caverns is a proven technology and makes it possible to store huge amounts of hydrogen with a relatively high storage efficiency at moderate costs [25][13]. Salt caverns can be constructed by pumping water into a salt dome, where subsequently saturated salt water is extracted. This process, depending of the size of the cavern, can take 2 to 3 years. In the Netherlands, there are currently five salt caverns constructed [13]. The costs of storage in a salt cavern is around 2.97 €/MWh [24][26].

2.3   Transportation

Hydrogen can be transported through existing gas pipes, usually at an operating pressure between 40 and 70 bar [13]. If natural gas pipelines are used for hydrogen transport, minor adjustments have to be made to prevent leakages and to increase the flow rate. Transport can also be facilitated by hydrogen tanks, which can be transported by ships or trucks. At high pressure, more hydrogen can be transported, therefore the operational pressures of hydrogen tanks varies between 200 and 700 bar [13].

2.4   Conversion

As conversion technologies fuel cells, hydrogen boilers and hybrid heat pumps are discussed. All three technologies can provide heat to the built environment.

Fuel cell

Fuel cells are similar to electrolysers, but operate in reverse mode. Instead of using electricity, it produces it by using hydrogen and oxygen [27]. During this process heat is being released. The working principle of a fuel cell is presented in Equation 2.8 [28]. The options available for fuel cells are identical to the options

available for electrolysers, namely the Alkaline Fuel Cell (AFC), Polymer Electrolyte Membrane Fuel Cell (PEMFC) and the Solide Oxide Fuel Cell (SOFC).

$$H_2 + \frac{1}{2}O_2 \rightarrow H_2O + \text{(electrical power + heat)} \qquad (2.8)$$
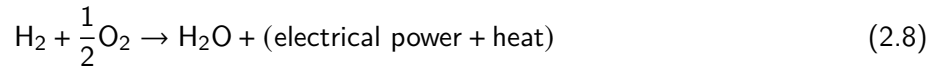
Hydrogen boiler

Conventional boilers can not be reused for nor adapted to hydrogen, but need to be replaced by hydrogen boilers. Currently, the first hydrogen boilers are installed for a pilot in Rozenburg [29]. It is assumed that this hydrogen boiler could achieve about the same efficiency as a conventional boiler, which is approximately 95%. In addition, it is expected that hydrogen boilers cost the same as conventional boilers.

Hybrid heat pump

As the name implies, this technology combines two technologies. In this case a heat pump closely cooperates with a hydrogen boiler. Most of the heating demand is supplied by the heat pump, where heat is generated by electricity. At times where heat supplied by the heat pump is insufficient, the hybrid heat pump switches to the hydrogen boiler. A hybrid heat pump reduces the hydrogen demand with 50 - 80 % compared to a hydrogen boiler [30]. However, this technology is not commercially available yet.

Chapter 3

Methodology

This section provides a general overview of the methodological steps taken to answer the research question. Firstly, the scope and assumptions are discussed, followed by three concepts. The proposed concepts are used as a guideline in this study.

3.1 Scope and assumptions

As previously mentioned, the Dutch government has the objective to achieve a decrease of 95% in CO_2 emissions by 2050. For the Dutch built environment the aim is to develop a carbon neutral or even an energy-producing built environment by this time. An important step in reaching this goals is to make the built environment free of natural gas. DWA would like to contribute to this development and advises its clients how to create a gas-free heat supply system. This study is commissioned by DWA, therefore it is important that the proposed research corresponds with DWAs aim and with the targets of the Dutch government. For this purpose the following considerations should be taken into account.

- The Dutch government wants be off the gas by 2050. It is imperative the analysed technologies should be operational by 2050, which is within 30 years as 2020 is the base year for this analysis. This implies that technologies should be or almost be in the commercial phase by now.

- This study focuses on sustainable heating in the built environment. Therefore, electricity use in the built environment is not included in the analyses. However, if electricity is used for heat supply, only sustainable electricity is considered.

- The aim of DWA is to provide the built environment with sustainable heat supply systems as alternatives for natural gas. Therefore the analysed technologies must operate fully renewable. This means that grey and blue hydrogen production technologies are not evaluated in this study.

- In the Netherlands, local energy production is preferred over import of energy from other countries [31]. If the government has the objective to be independent in their energy supply system, large-scale import of hydrogen or electricity will have a counteract effect. Therefore, this study only assumes the use of local generated sustainable energy.

3.2 Concepts

In order to answer the main question and sub-questions in this research, two concepts were proposed: (I) available green hydrogen for the built environment and an (II) economic assessment which indicates the cost for a hydrogen heating system per type of building. The first concept discusses the method used for determining whether it is feasible to substitute the total natural gas use of the Dutch built environment by hydrogen, which gives an answer to sub-question I. The second concept provides the methods used to answer sub-question II. In this concept the classification of the built environment and the economic assessment that is executed to determine the costs for a hydrogen heating system per type of building is discussed. The outcomes can be used to determine if a hydrogen heating system is competitive with alternative gas-free options for heat supply. Based on both concepts a vision is outlined of the role of hydrogen in the built environment, which is the main question in this study.

3.2.1 Available green hydrogen for the built environment

The built environment is not the only sector that has to complete this difficult task in the energy transition. Other sectors have to decarbonise as well, and may also want to make use of green hydrogen. For example, sectors that currently use grey hydrogen or sectors that use fossil fuels. In this study, it is assumed that sectors which currently use grey hydrogen will have precedence over the built environment, as they have fewer sustainable alternatives available as the hydrogen is used as end-product instead of heat. This section describes the method used to calculate the renewable electricity production to substitute the natural gas use in the built environment and the current grey hydrogen consumption by other sectors. Based on this outcome, the amount of green hydrogen available for the built environment is determined. The following data is required to perform the analysis: (I) current hydrogen use per sector, (II) current natural gas use for heat provision in the built environment, (III) efficiencies of technologies in the hydrogen chain and (IV) operational schedules of Dutch solar panels and wind turbines. The required data is obtained through an extensive literature review.

Hydrogen energy system

Firstly, the hydrogen energy system should be analysed, as this system differs per sector and required end product. In case hydrogen is required as end product, it is assumed that the supplied hydrogen can be used directly, also referred to as a demand response supply system. In this case the demand is adjusted to the supply instead of vice versa. If hydrogen is used for heat production, which is the case for the built environment, the demand is specific to the heat demand profile of the end user. It is therefore necessary to implement a storage technology in the proposed energy system to satisfy demand at all times.
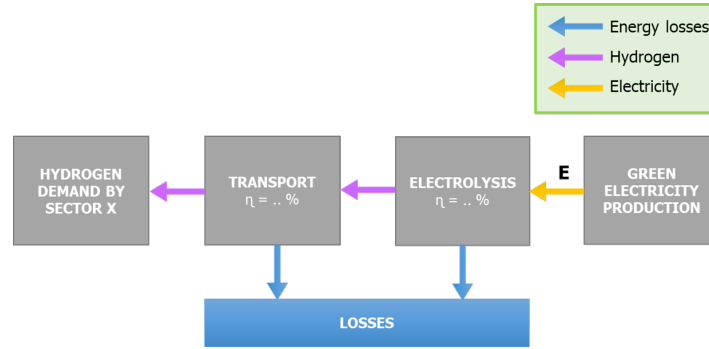
Figure 3.1: Schematic view of an energy system producing green hydrogen, including transportation and production of hydrogen from green electricity to hydrogen.

Figure 3.1 shows the proposed energy system for hydrogen production for sectors that use hydrogen as end product. In this case only energy losses by electrolysis and transport are being accounted. Equation 3.1 can be used to calculate the quantities of green electricity needed to supply the hydrogen ($E_{H_2,annual}$), which is based on the system proposed in Figure 3.1.

$$E_{el,green,annual} = \frac{E_{H_2,annual}}{\eta_{electrolysis} \cdot \eta_{transport}} \tag{3.1}$$
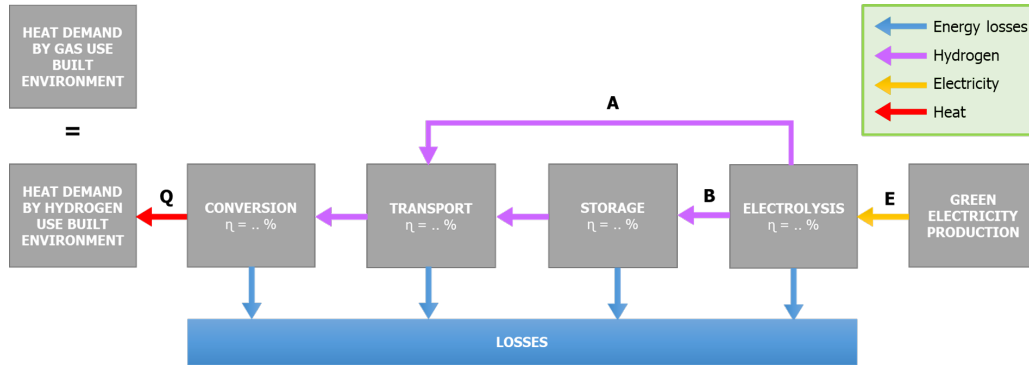
Figure 3.2: Schematic view of an energy system producing heat by green hydrogen, including conversion, transportation, storage and production of hydrogen from green electricity to heat.

As starting point for the Dutch built environment, the heat demand based on the natural gas use should be equal to the heat supplied by the hydrogen energy system as shown in Figure 3.2. To determine the required amount of renewable electricity, the production path needs to be followed. Each step in this hydrogen system involves energy losses (Figure 3.2). Equation 3.2 shows the formula that is used to calculate the annual green electricity ($E_{el,annual\ green}$). In case supply does not correspond with the demand, part of the hydrogen produced is stored. In this case η represents the efficiency and Q the total annual heat demand by hydrogen. $\phi_{direct\ use}$ represents the fraction hydrogen that can be used directly and ϕ_{stored} the fraction that needs to be stored. The values of $\phi_{direct\ use}$ and ϕ_{stored} differ depending on the electricity supply profiles for different renewable energy sources. The method that is used to determine these fractions is discussed in the next section.

$$E_{el,green,annual} = \frac{\phi_{direct\ use} \cdot Q_{demand,annual} \cdot \eta_{storage} + \phi_{stored} \cdot Q_{demand,annual}}{\eta_{conversion} \cdot \eta_{storage} \cdot \eta_{electrolysis} \cdot \eta_{transport}} \tag{3.2}$$

Stored and direct use fractions   Renewable energy sources, like solar and wind power, are not consistent, nor controllable. The wind does not blow all the time in the Netherlands. Likewise, solar radiation that hits photo voltaic panels and produces electricity is affected by nightfall, clouds and the geographical location. Power production can not be adjusted according to demand, which means storage is required. This analysis examines the extent to which sustainable electricity production converges with a heat demand profile of the built environment. Alongside hydrogen production, this analysis is also relevant in case of electrification of heat. A rough estimate is made for the proportions of direct use and storage for the built environment. For this purpose, renewable electricity supply profiles (e.g. wind and solar power) and a heat demand profile of a building are needed as input data. To perform this analysis, modelled wind power profiles are used obtained from Nick Nortier of University Utrecht. The hourly electrical output is modelled based on the expected wind turbines present by 2030. Three scenario's were performed: local (high degree of decentralisation), national (high degree of centralisation) and regional (mixed local and national). For this analysis, the modelled profiles of the regional strategy are used, as it is a combination of two extremes. Figure A.1 of Appendix A shows a map of the Netherlands with the locations of the onshore and offshore wind turbines expected by 2030. The electrical output is based on the meteorological input of 2017. In addition, this analysis is also performed for solar power. Electricity generated from solar is effected by the orientation and location of the panel. For solar, a profile has been set up based on the average hourly solar irradiance (years 2015 - 2019) in 'De Bilt', obtained from KNMI [32]. For this analysis, it is expected that the solar panels are horizontally orientated. Lastly, a heat demand profile of an average building is obtained from DWA. The wind turbine and solar profiles are presented in Appendix A, Figure A.2.

A standardised profile of the electricity production and heat demand is drafted by using Equation 3.3 and 3.4, where $\phi_{standardised\ profile}$ is the fraction of E or Q of annual E or Q at point t in time. Time frequency is set at one hour with a time frame of 8760 hours accounting for 1 year. Note that the energy losses due to storage are not considered in the fraction calculation, even as the time to complete the entire system from E to Q. However, this does not cause for major differences in the outcome as the storage losses for hydrogen storage technologies are relatively low and the system response of the electrolyser is relatively high (milliseconds to seconds).

$$\phi_{standardised\ profile\ electricity\ supply,t} = \frac{E_{el,green,t}}{E_{el,green,annual}} \tag{3.3}$$

$$\phi_{standardised\ profile\ heat\ demand,t} = \frac{Q_{demand,t}}{Q_{demand,annual}} \tag{3.4}$$

$$\phi_{storage,t} = \phi_{standardised\ profile\ electricity\ supply,t} - \phi_{standardised\ profile\ heat,t} \tag{3.5}$$

By applying Equation 3.5 the fraction storage can be determined. Figure 3.3 shows an example of a standardised demand and supply profile of 1 day. The sum of all fractions stored is equal to the sum of all fractions used from storage if storage efficiency is assumed to be 100%. Making that the area direct use plus stored is equal to 1 over 1 year. This ratio allows to determine the fraction stored using Equation 3.6.
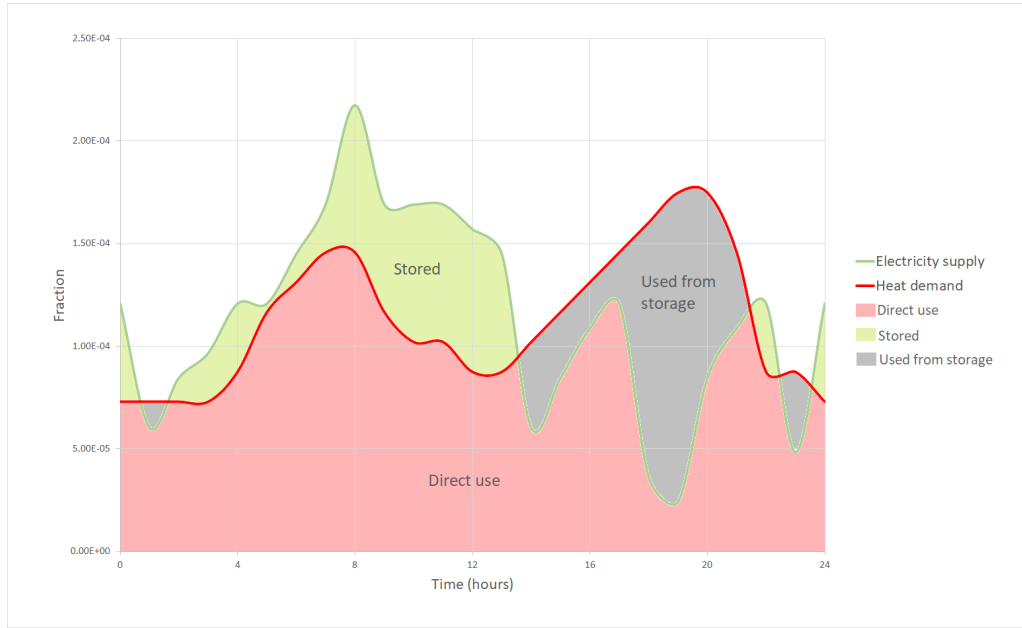
Figure 3.3: Visualisation of the standardised heat and electricity supply profile to determine the fraction direct use and fraction stored. The direct use area is visualised in red, stored in green and used from storage in grey. In this case the green area is equal to the grey area if a time frame of 1 year is used. In this figure one particular day is displayed.

The fraction stored (ϕ_{stored}) can be calculated by adding up all positive values of $\phi_{\text{storage,t}}$, which is equal to the stored area in Figure 3.3. By applying Equation 3.7 the fraction direct use ($\phi_{\text{direct use}}$) can be determined.

$$\phi_{\text{stored}} = \sum_{t}^{T} \phi_{\text{storage,t}} \rightarrow \text{if } \phi_{\text{storage,t}} \geq 0 \tag{3.6}$$

$$\phi_{\text{direct use}} = 1 - \phi_{\text{stored}} \tag{3.7}$$

The outcome of this analysis can be used as an indication to determine the amount of storage needed if renewable electricity is used as primary energy source for heat provision in the built environment. The input data used can be influenced by many factors and specific to locations, behaviour and policies. Therefore, further research is required to validate the outcome. However, this is beyond the scope of this study.

Size and area   To get an idea of the amount of renewable electricity that needs to be generated to produce hydrogen for these sectors, the electricity demand is expressed in the share of total wind turbines by 2030 and km^2 of solar panels. For this analysis the previously mentioned modelled wind turbine profiles are used (Section 3.2.1), as they represent the expected installed wind turbine capacity by 2030. The onshore wind turbine profile is based on 2615 wind turbines with each an average capacity of approximately 3MW, where the offshore wind turbine profile is based on 1151 wind turbines with each an average capacity of approximately 9 MW. The electrical power produced by 1 m^2 of solar panels is on average 150 kWh/year [33]. This value is used to calculate the area occupied for solar panel installation to produce the expected hydrogen needed per sector.

3.2.2 Economic assessment

Energy saving measures differ per building as well as the costs involved to make a home free of natural gas. Therefore, the built environment is divided into different types of buildings. The building types are classified according to the *Voorbeeldwoningen 2011 - bestaande bouw* (Dutch exemplary buildings 2011 - existing buildings) [34]. The Dutch built environment is classified in 30 buildings based on type of building and construction year. It contains 7 building types: Vrijstaande woning (Detached house), 2 onder 1 kap woning (Semi-detached house), rijwoning (terraced house), maisonettewoning (maisonette), gallerijwoning (apartment with a gallery as entrance), portiekwoning (apartment with a porch as entrance) and flatwoning (flat), and the construction years are divided into periods of 10 to 15 years. This technical report provides a theoretical basis, as the architectural and installation technical characteristics of each exemplary house is described. These 30 buildings together reflect the total Dutch housing stock, up to buildings with 2005 as construction year. This classification is often used to support policy advice on energy saving measures, what makes it an appropriate base to perform the economic analysis. DWA also sticks to this division of the built environment in their analyses for their clients. In table 3.1 the classification of the built environment is presented.

Table 3.1: Classification of the Dutch built environment based on the 'Voorbeeldwoningen' of RVO. A distinction is made based on type of building and construction year, which in total are 30 residential building types.

Vrijstaande woning	2 onder 1 kap woning	Rijwoning	Maisonette- woning	Gallerijwoning	Portiekwoning	Flatwoning
-	-	< 1945	-	-	< 1945	-
< 1964	< 1964	1946 - 1964	< 1964	< 1964	1946 - 1964	< 1964
1965 - 1974	1965 - 1974	1965 - 1974	1965 - 1974	1965 - 1974	1965 - 1974	1965 - 1974
1975 - 1991	1975 - 1991	1975 - 1991	1975 - 1991	1975 - 1991	1975 - 1991	1975 - 1991
1992 - 2005	1992 - 2005	1992 - 2005	1992 - 2005	1992 - 2005	1992 - 2005	1992 - 2005

For each type of building the energy performance is modelled by Netherlands Enterprise Agency (RVO) for the current status of the building and for a proposed energy saving package [34]. For a clear overview, it is recommended to consult the document '*Voorbeeldwoningen 2011 - bestaande bouw*'[35], which also contains the energy performance data per building that is used for this analysis. In case an energy saving package is applied the energy label of the house is improved to an A or B label, however this differs per building. The energy saving package contains floor, wall and roof insulation. The costs insulation per building element are presented in Appendix B.1.1 Table B.2. However, hydrogen is a high energetic energy source, which can be applied to houses without insulation. Nonetheless, DWAs main purpose is to limit total energy consumption in the built environment. Therefore the economic assessment is performed for two cases, namely (I) a hydrogen heating system in the current status of the building, as well as (II) a hydrogen heating system in combination with the proposed energy saving package by RVO.

Total Cost of Ownership

As previously mentioned, the economic assessment is performed for two cases. For each type of building and case a Total Cost of Ownership (TCO) is calculated. This economic indicator allows to compare the costs of the proposed systems with alternative gas-free options and is often used by DWA. The TCO per residence is calculated over a period of 30 years, which is seen as the lifetime cost of the investment by DWA. This indicator includes all investment costs, operation and maintenance costs and required reinvestment over the selected period. The TCO is presented in €. To calculate the TCO, the following formula is proposed (Equation 3.8). The capital expenditures (CAPEX) represent the investment and reinvestment costs. This includes cost for a hydrogen heating system, installation costs and charges for adjusting the network from natural gas to hydrogen. For case II costs for insulation are also included in this component. In case the lifetime of the investment is shorter than the proposed time frame, a reinvestment has to be made. The sum of X indicates the sum of investments, indexed by the year of expenditure. Operating expenditures (OPEX) represent the annual costs over the time frame (T). The OPEX includes costs such as hydrogen supply costs, network costs, taxes and maintenance costs. The hydrogen supply costs and taxes depend on the annual energy consumption, which is different per type of building. The TCO is indexed by α, where s represents the inflation and r represents the discount rate (Equation 3.9). In this case n is the number of periods to a specific year between 1 and T. All cost components in Equation 3.8 are presented in € excluding VAT.

$$\text{TCO} = \sum^{X} \alpha_t * \text{CAPEX}_t + \sum_{t=1}^{T} \alpha_t * \text{OPEX}_t \tag{3.8}$$

$$\alpha = \left(\frac{1+s}{1+r}\right)^n \tag{3.9}$$

A hydrogen boiler is assumed as hydrogen heating system. In addition, the hydrogen supply costs are based on Dutch green hydrogen, generated by renewable electricity in the Netherlands. However, since Dutch green hydrogen is not commercially available yet, an estimate is made for the current price and price development over the years. Assumptions are made for the supply costs, network costs and taxes, which are based on technical reports or equated to natural gas. However the price development of hydrogen is rather uncertain. Therefore different price scenarios are performed. Figure 3.4 gives a schematic overview of the executed scenarios. As hydrogen districts are already being built, in scenario A the TCO is examined for a switch to a hydrogen heating system by 2020. Given green hydrogen production is relatively new and hydrogen supply costs rather high, the hydrogen heating systems are probably more affordable over a decade. Therefore, scenario B assumes a price drop over 10 year and assumes a switch to a hydrogen heating system by 2030. Lastly, even though the Netherlands wants to be independent in their energy supply, scenario C assumes hydrogen import from the Sahara, at a cost of 1 €/kg. This is a hypothetical scenario as hydrogen is not available at this price yet, neither the possibility of transport.
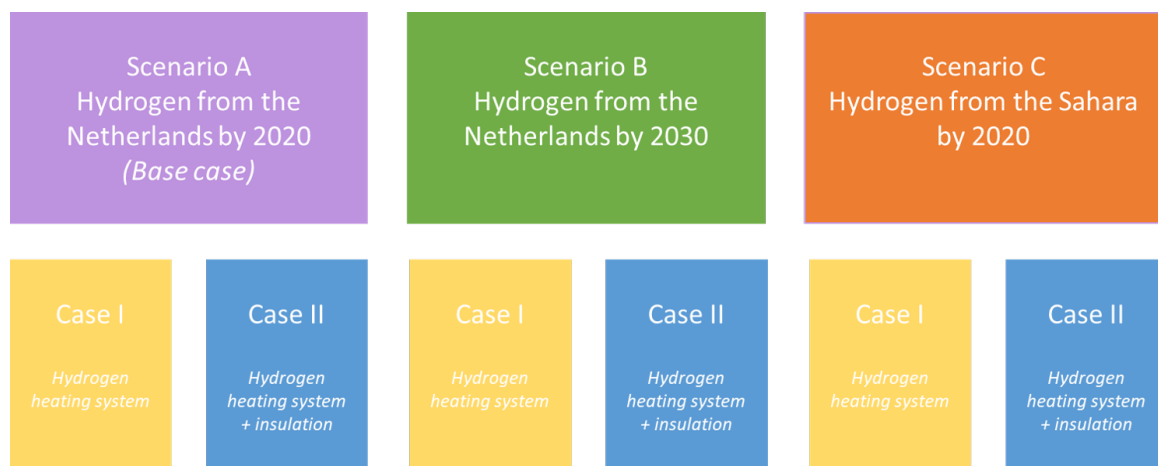
Figure 3.4: Schematic overview of the 3 performed price scenarios for the economic assessment. For each scenario a case I and case II is executed.

Chapter 4

Results A - Available green hydrogen for the built environment

In 2018, approximately 163 PJ of hydrogen was used as feed stock in the chemical industry [36]. However, the hydrogen used by the chemical industry is currently produced as grey hydrogen. In the near future, this production process needs to be transformed to a sustainable process, as there is no other sustainable alternative available for hydrogen needed by the chemical industry. This is not the case with the built environment as this sector has apart from hydrogen alternatives available for heating . Therefore, the chemical industry should have precedence over the built environment in the availability of hydrogen for these sectors. This study investigates the substitution of natural gas by hydrogen in the heat provision of the built environment, therefore the current amount of heat provided by natural gas in this sector sho also included in the hydrogen demand. The final natural gas use for heat production in the built environment was 408 PJ by 2018 [37].

4.1 Chemical industry

As mentioned in the previous section, the current hydrogen demand of the chemical industry is 163 PJ, which is equal to the supplied hydrogen to the end user (Hydrogen chain in Figure 3.1). To reduce losses, it is expected that renewable electricity is produced in industrial areas. As electrolyser, the PEMEC is most likely the most advanced technology in the near future, as subsidies are already being applied for construction of large-scale PEMECs. The PEMEC efficiency is expected to be between 77% and 88% by 2030, depending on the system load. On the assumption that the electrolyser has an average system load of 50% over the year, the efficiency is approximately 83% by 2030 [23]. In Appendix A Figure A.3 the efficiency of the PEM is plotted against the system load. However, today PEMEC efficiency is still around 70%, which is included as lowest value in the sensitivity analysis [24][21]. Multiple studies expect the energy losses through pipeline transport between 2% and 5% [26][36]. Therefore, a transport efficiency is accounted of 98%, considering the short distance pipes since the electrolyser will likely be installed in the industrial park. Based on these assumptions, the annual renewable electricity generation is approximately 200 PJ. The sensitivity of the outcome is tested. In this analysis, the annual hydrogen demand and the transport and electrolyser efficiency of the system are assessed (Figure 4.1). In the worst case, a low PEMEC efficiency

results in an increase of approximately 37 PJ of renewable electricity demand, while in an optimal scenario this causes for a decrease of 11 PJ. This graph has no equal slope, given the outcome also depends on the transport efficiency. Transport efficiency varies between 90% and 99%, which has about the same effect as the efficiency of the electrolyser. As expected, in both cases an increase in efficiency positively influences the outcome, while an increase in demand results in the opposite.

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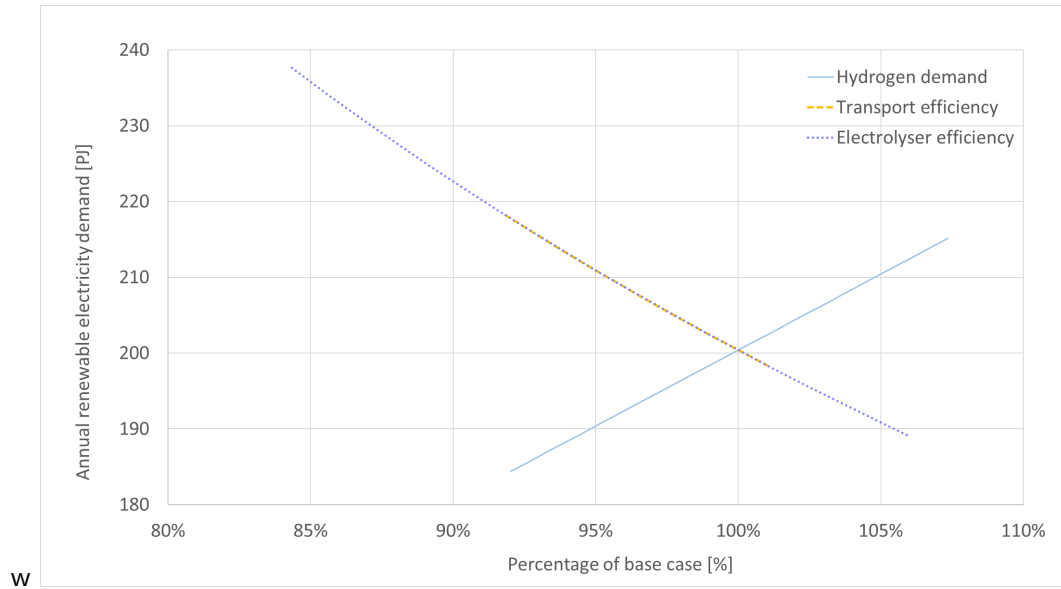
Figure 4.1: Sensitivity of the annual renewable electricity demand for hydrogen production for the chemical industry. The sensitivity of the outcome is tested for the following input parameters: hydrogen demand, electrolyser and transport efficiency.

4.1.1 Size and area

To supply 163 PJ of hydrogen to the chemical industry, an area of 371 km^2 for solar panels is needed. This is an area the size of Rotterdam. For 1 PJ of hydrogen, 2.27 km^2 area is required for solar panel installation. In Figure 4.2 the size of solar panels is visualised in purple. However, if the electricity is produced by onshore wind, the expected total onshore wind capacity by 2030 needs to be more than doubled. In total 5878 of 3MW onshore wind turbines should produce the required amount of electricity, which means that per 1 PJ of hydrogen 36 wind turbines are needed. This analysis indicates that the expected installed capacity of onshore wind turbines by 2030 is far from enough to produce the hydrogen needed by the chemical industry. With regard to the total expected on and offshore wind turbines by 2030, the chemical industry will take up approximately 74% of the total installed capacity. Given the extremely large surface of solar panels or amount of wind turbines, it is already quite a challenge to produce sustainable hydrogen for the chemical industry. Not to mention that the demand of the built environment still have to be added. This analysis indicates that there is actually no electricity available to produce green hydrogen for the built environment.

Figure 4.2: Map of the Netherlands, where the purple dot represents the area for solar panel installation to supply 163 PJ of green hydrogen to the chemical industry. It is assumed that the annual production of the solar panels is 150 kWh/m^2.

4.2 Built environment

As can be derived from Figure 3.2, the amount of renewable electricity needed for hydrogen production in this sector can be calculated by using the conversion-, transport-, electrolyser- and storage efficiency and direct use/storage ratio. Firstly, storage and direct use fractions are determined, followed by the efficiencies of the technologies and processes in the hydrogen energy system and lastly the calculated expected amount of renewable electricity production.

4.2.1 Storage and direct use fractions

The methods used for this analysis are discussed in Section 3.2.1. Three different renewable energy sources are analysed; onshore wind, offshore wind and solar. The standardised profiles are shown in Figure 4.3. Based on these figures, the following points should be noted. The mismatch between the heat demand and electricity supply for wind turbines for both on and offshore is fairly gradual, but is increasing towards winter. For solar panels it has just the opposite effect. These results are to be expected based on the fact that heat demand during winter is higher, solar irradiance is higher in summers and wind energy pattern is relatively constant over the year, even though wind speeds increase slightly towards winter. Table 4.1 shows the annual

mismatch and the maximum energy stored per source as percentage of the annual hydrogen demand. The annual mismatch indicates how much energy needs to be stored to satisfy the heat demand of the built environment over the year. The maximum energy stored shows the maximum energy stored at least at one point in time. This percentage relates to the minimum capacity of the storage facility. Optimisation of this value can reduce storage costs. As can be concluded from Table 4.1, the mismatch for wind turbines is much lower than for solar. This indicates that wind power converges better with the heat demand of the built environment than solar energy does. The results actually show that it is energetically more advantageous to use Dutch wind power, than to use solar energy for heat provision in the built environment. Also, a combination of on and offshore wind power works positively for the degree of similarity between the supply and demand. Given this outcome, the next paragraph examines whether a combination of onshore, offshore and solar can improve this value even more. These values indicate which kind or which mixture of renewable electricity generating technologies can be deployed in the most efficient way for heat supply in the built environment.

Table 4.1: The stored energy and the maximum energy stored at one point in time as a percentage of total annual energy supply.

Source	Annual mismatch	Maximum energy stored
Onshore wind	47.7 %	4.2 %
Offshore wind	46.9 %	6.6 %
Dutch on and offshore in 2030	46.6 %	5.8 %
Solar	70.4 %	25.6 %

Optimal shares A combination of wind and solar energy could decrease the mismatch between the supply and demand profiles. Therefore an optimisation is performed in Excel with the integrated solver. The optimisation is performed by minimising the mismatch, this by varying the share of solar, onshore and offshore wind. As a result, the annual mismatch is reduced to 46.3%, if the ratios of electricity supply consist of 7,4% solar, 53.7% offshore and 38.9% onshore. The related maximum energy stored is 6.8%, which means that at least at one point in time 6.8% of the annual produced hydrogen is stored. However, it is questionable whether the benefits of the reduced annual mismatch (decrease in losses through storage) out weight the increase in storage capacity. Therefore an optimisation is performed, minimising the maximum energy stored. As a result, the storage capacity can be minimised by using 100% onshore wind.
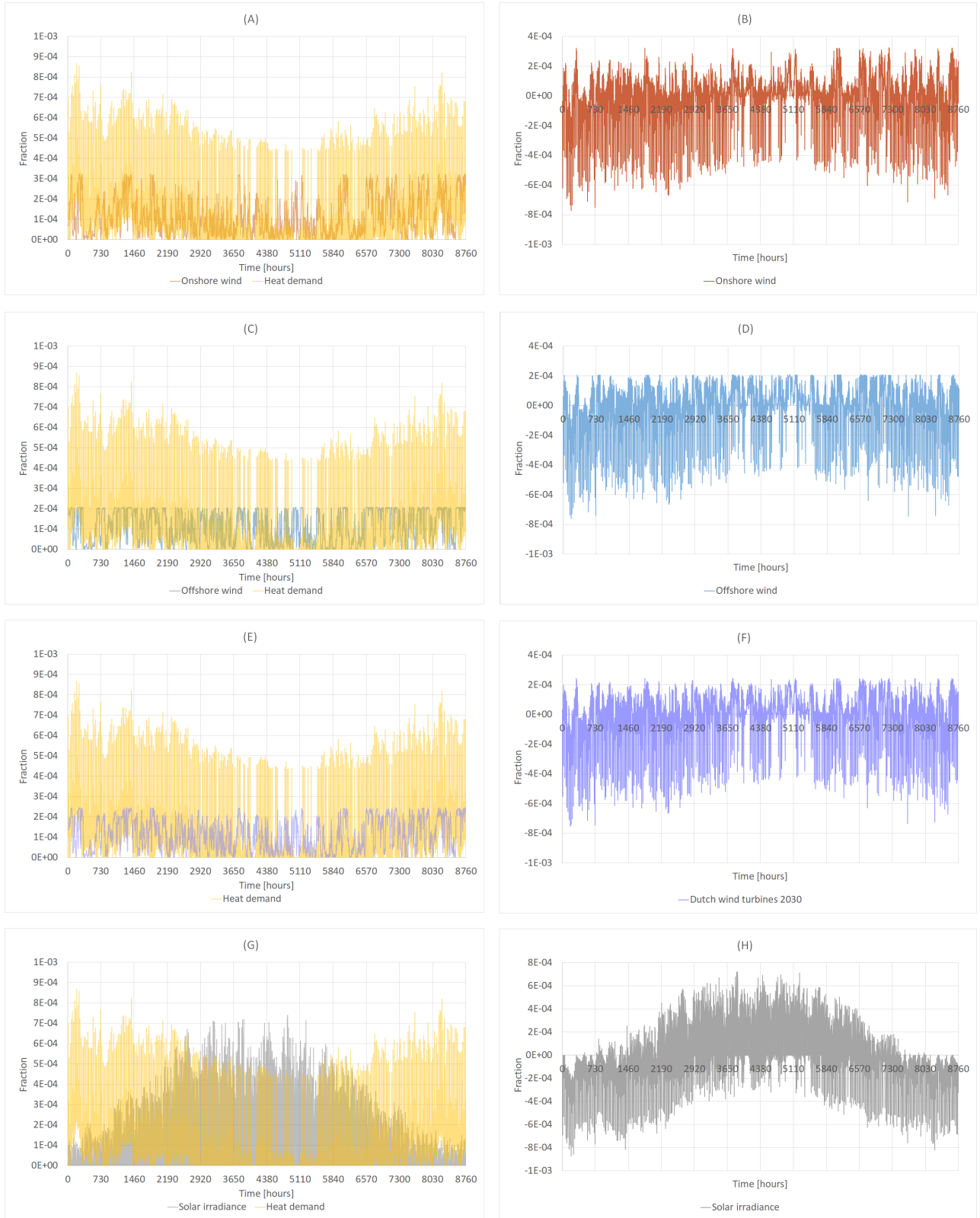
Figure 4.3: Standardised profiles with Graph (A) being onshore wind, (C) offshore wind, (E) Dutch onshore and offshore wind and (G) solar irradiance, where Graph (B), (D), (F) and (H) show the mismatch between the heat demand and proposed sources respectively.

4.2.2 Hydrogen energy system

As a starting point, the final natural gas consumption of the built environment should be known. In 2018, the natural gas consumption in the built environment was 408 PJ. For this analysis, it is assumed that the built environment uses hydrogen boilers as conversion technology. Expected is that this boiler can achieve an equal efficiency as the tradition natural gas boiler. With reference to the hydrogen energy chain (Figure 3.2), the final natural gas consumption equals to the amount of hydrogen before conversion to the end users. With regard to the used transport efficiency, there is assumed that the hydrogen is produced on a central level. Therefore, the upper value (95%) is applied for this analysis. The electrolyser efficiency is expected to be 83%, identical to the previous analysis. For storage, salt caverns are expected to be the common large scale storage technology in the future. The potential of salt caverns in the Netherlands is 43.25 TWh, mostly located in the north [13]. This potential is sufficient for hydrogen storage for the built environment based on the maximum energy stored value. Storage efficiency is expected to be 95% [24]. The storage and direct use fractions that are used are based on the optimal shares for reducing the mismatch. This means that a storage fraction of 0.463 is used and a direct use fraction of 0.537. The annual renewable electricity production for the proposed hydrogen system is equal to 530 PJ.

Identical to the outcome of the chemical industry, a sensitivity analysis is performed. Figure 4.4 shows the sensitivity of the outcome per input parameter. As can be seen the renewable electricity generation is not sensitive to the storage/direct use ratio, which indicates that the amount of energy stored does not have much effect on the amount of primary electricity needed. If solar energy would be used for renewable electricity production, an additional electricity production is needed of approximately 6 PJ. This means that an optimisation of minimising the maximum energy stored is probably more relevant in terms of costs, since this indicates the size of the salt cavern.
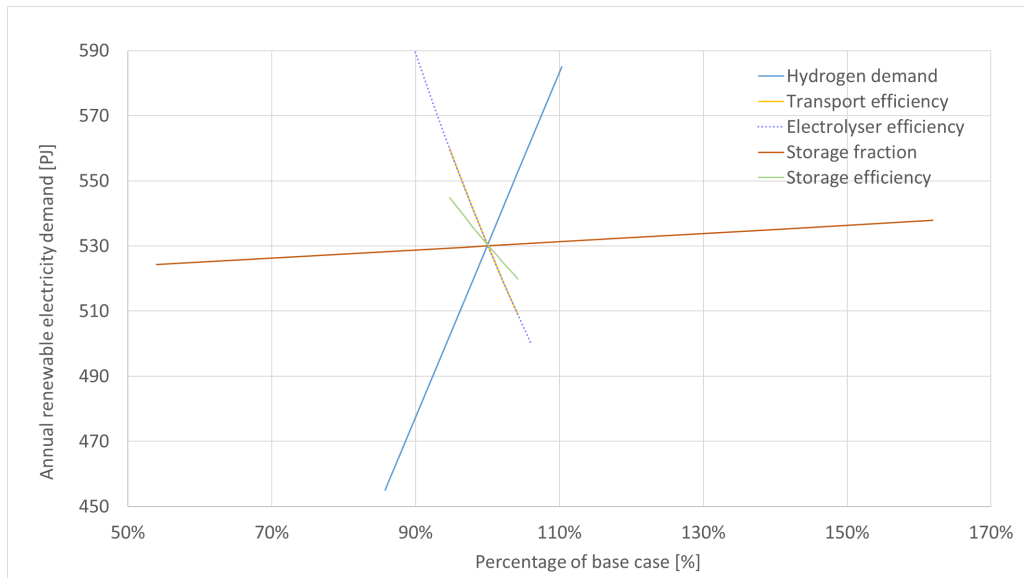
Figure 4.4: Sensitivity of the annual renewable electricity demand for hydrogen production for the built environment. The sensitivity of the outcome is tested for the following input parameters: hydrogen demand, storage/direct use ratio, electrolyser, transport and storage efficiency.

4.2.3   Size and area

In terms of size, an additional 686 km^2 of area is needed for solar installation to supply the current natural gas users in the built environment with green hydrogen. This area is about 3 times the size of Amsterdam. Figure 4.5 shows the surface needed for solar installation for hydrogen for the built environment in red and for the chemical industry in purple. If 408 PJ of green hydrogen is produced by onshore and offshore wind turbines, approximately 2 times of the total expected installed capacity by 2030 is needed. Clearly, this is not feasible and extremely unlikely that this amount of electricity will be allocated to hydrogen production for the built environment. Certainly if hydrogen is also required in the industry as feed stock and electricity use in the Netherlands also needs to be sustainable by 2050.
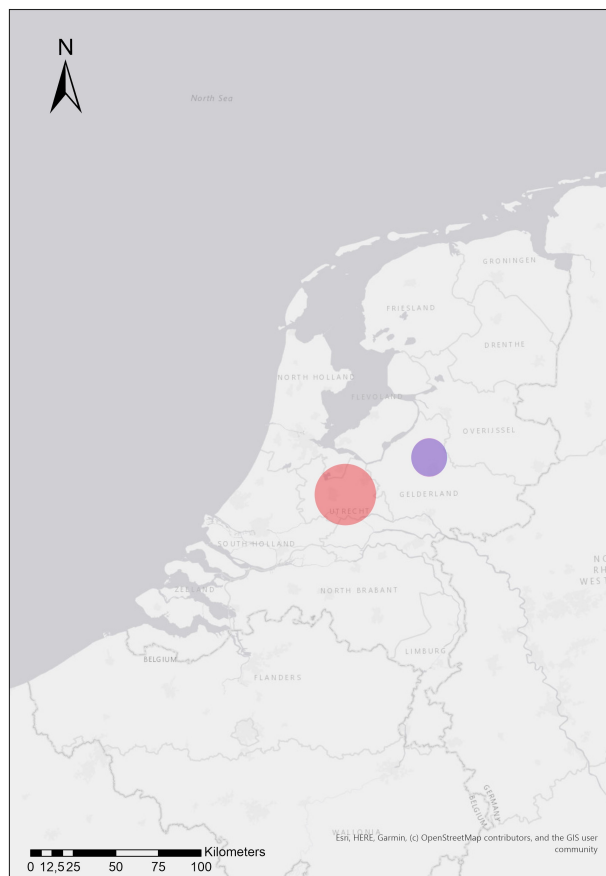
Figure 4.5: Map of the Netherlands, where the purple dot represents the area for solar panel installation to supply 163 PJ of green hydrogen to the chemical industry and the red dot shows the area needed to supply 408 PJ of hydrogen to the built environment. It is assumed that the annual production of the solar panels is 150 kWh/m^2.

Chapter 5

Results B - Economic assessment

Firstly, the economic parameters used to perform the economic assessment are discussed. Next, the total cost of ownership is determined for 3 scenarios where different hydrogen supply costs are applied. For this analysis a discount rate of 3% and inflation of 2% is used. The TCO is presented excluding VAT. The calculated TCO per house can be compared to the TCO of alternative natural gas-free options by DWA, as use of heat networks or all electric heat supply by heat pumps. In general, for an average building, the TCO for a heat network is estimated at € 37,000 and for all electric € 52,000.

5.1   Investment costs

For this analysis, a distinction is made based on type of building and construction year according to the example homes [34]. Case I describes the costs for a hydrogen heating system if no energy saving package is applied, where case II a basic energy saving package is applied. The data that is used to perform this analysis is obtained from *Voorbeeldwoningen 2011 – EPA detailgegevens per woningtype, subtype en bouwperiode* [35]. This report contains housing characteristics, input data for Energy Index calculations and overviews with calculation results for all sub types. For case I, investment costs contain the costs for the hydrogen boiler, cost for installation plus costs to adjust the gas network. Investment costs for case II includes previous mentioned costs and costs for insulation. The costs for insulation are obtained from the report [35]. Expected is that the hydrogen boilers have a lifetime of 15 years and have the same price as the conventional HR boilers, namely € 2,094 excluding VAT . After 15 years a reinvestment is made of € 1,818 excluding VAT (assuming that price will drop by 10 % over 15 years). For installation of the boiler 10% of the investment price is accounted. In addition, a cost of € 205 for adjusting the natural gas network to hydrogen is included in the investment costs [38].

5.2   Annual costs

The annual costs include energy and maintenance costs of the system. The energy costs depends on the energy consumption and the hydrogen supply cost. The energy consumption has been derived from the report [35], where the hydrogen price is discussed in the next section. Maintenance costs are assumed to be € 120 per year, this is fairly high compared to a conventional HR boiler as additional maintenance is

required for the hydrogen boiler in order to prevent leakages.

5.2.1 Hydrogen price

There is a lot of debate about how the price of hydrogen will develop, both on the (I) cost of the production chain, as well as (II) taxes and (III) costs for network operators and how these cost will be allocated to the end-user. All three components are discussed below. In general, current natural gas bills consists of 43% supply costs, 13% costs for the grid operator and 44% taxes [39].

Hydrogen supply costs   The hydrogen supply costs contain hydrogen production cost and a percentage of profit for the supplier. Recent studies suggest that production costs for hydrogen could drop to 1 €/kg by 2030. This expectation is made based on up-scaling, technological innovation and low cost of solar electricity production, for example in the Sahara. However, in case green hydrogen is produced by Dutch renewable electricity, costs are likely to be higher. A recent study of CE Delft estimates the integral production chain cost of green hydrogen generated by Dutch solar panels and wind turbines at approximately 5.24 €/kg (0.1572 €/kWh) by 2017 [40]. The calculation of the supply costs include; costs for renewable electricity, electricity storage cost, electrolyser costs, hydrogen storage and costs for local distribution to a network [40]. Expected is cost will decrease, due to lower prices for Dutch renewable electricity and increasing full load hours of the PEM electrolyser. Based on the price development described in this study, it is assumed that the hydrogen production price will drop to 2.50 €/kWh (0.075 €/kWh) by 2050. An expectation is made for the price development of hydrogen between 2020 and 2050. If an exponential decrease in price is assumed, the hydrogen production price is equal to $0.1572 * 0.976^{2017-T}$, where T is a specific year after 2017. Figure 5.1 shows the hydrogen price development based on this formula and the discounted hydrogen price over time. Besides the production costs, the energy supplier charges costs for transportation and profit. If the percentage of profit is equated with that of natural gas, this cost item is equal to 30% of the supply costs. However, for hydrogen supply, a profit margin of 20% is assumed, given the high costs of hydrogen production. This means that supply costs of hydrogen is expected to be 0.1825 €/kWh including margin supplier by 2020 (0.1460 €/kWh excl. margin) as can be seen in Figure 5.1.

Taxes   Tax is also part of the energy costs for the supply of natural gas. Currently, energy tax (EB - Energie Belasting) and renewable energy storage (ODE - Opslag Duurzame energie) is charged for natural gas [41]. The EB is equal to 0.3331 €/Nm^3, where the ODE is 0.0775 €/Nm^3 of the total delivered quantity of natural gas supplied. However, the question remains whether taxes will be levied on hydrogen. For this analysis, it is assumed that these taxes are equal to natural gas. When this is standardised by energy content of natural gas instead of the volume, the energy tax for is 0.0338 €/kWh and storage renewable energy equals 0.0082 €/kWh. The tax is standardised by energy content instead of volume as the energy content per volume of hydrogen is much smaller than that of natural gas.
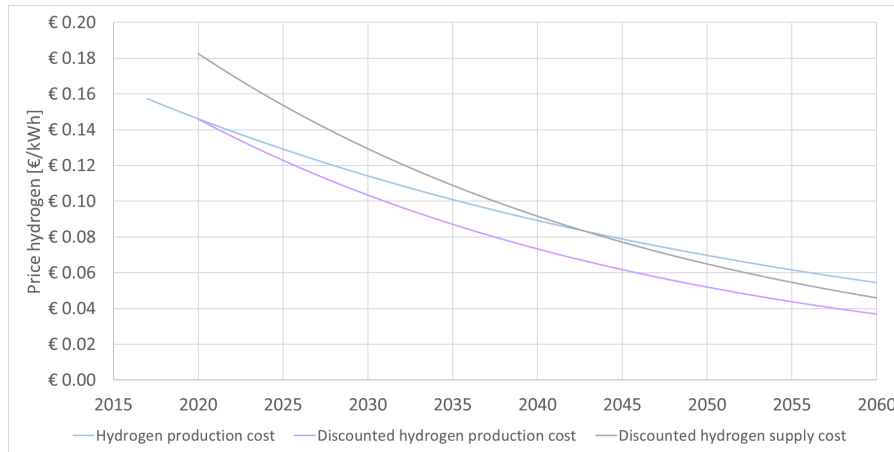
Figure 5.1: Graph of the hydrogen production costs and discounted hydrogen production costs presented based on the exponential price drop of 0.976^{2017-T}. It also contains the expected hydrogen supply costs including 20% profit for the hydrogen supplier.

Network costs   Network costs consist of (I) standing charge, (II) capacity tariff, (III) periodic connection fee and (IV) metering tariff. For an average household, total costs are € 150 excluding VAT [42]. Most likely network costs will increase if hydrogen is transported to the existing natural gas pipelines [38], as the transfer rate has to be increased, the measuring system needs to be adjusted, more inspection is needed to prevent leakages. Most of the costs that have to be made for the adjustment are one-time charges. However, these costs are already included in the investment costs. However, it may happen that an additional annual cost of € 20 will have to be charged as additional inspections for excavation work is needed and € 100 for inspections of the indoor gas installation. However, the need for these measures is still debatable, therefore it assumed that 25% of the proposed costs is charged (€ 40).

5.3   Total Cost of Ownership

The Total Cost of Ownership is performed for 3 scenarios, namely: Scenario (A) Hydrogen from the Netherlands by 2020, (B) Hydrogen from the Netherlands by 2030 and (C) Hydrogen from the Sahara by 2020. For each scenario the TCO of case I and case II is determined. As previously mentioned, in case I no energy saving package is applied to the houses and the current heating system is replaced by a hydrogen boiler. For case II, a basic energy saving package is applied to the houses and the current heating system is replaced by a hydrogen heating system with a hydrogen boiler, same as in case I. The sections below elaborate on the TCO of the 3 proposed scenarios and the assumptions made to perform the analysis. The deployment of a hydrogen heating system is the most convenient in buildings where insulation costs are not being returned by the benefit of energy saving.

5.3.1   Scenario A - Hydrogen from the Netherlands by 2020

The above mentioned parameters are used to perform this analysis. Year 2020 is assumed as base year. This means that a reinvestment for the hydrogen boiler is made by 2035. Expected is that by 2035, the hydrogen

boiler will cost € 1,886 (10% price drop compared to 2020, 0,67 % per year). The cost breakdown per type of building for case I is presented in Figure 5.2 and for case II in Figure 5.3.

Figure 5.2: TCO over 30 years and the average annual costs for case I of scenario A presented per building. The costs are divided into four cost components, namely (I) investment and reinvestment, (II) energy costs which contains supply costs and network costs, (III) taxes and (IV) maintenance costs. If taxes are not applied to hydrogen, this cost component can be excluded. The error bars represent an error margin of 10%.

From an economic perspective, if case I is applied, a hydrogen heating system is extremely expensive for homes with old construction years especially for non-stacked buildings. For example, a detached house has to pay approximately 6,000 €/year, which means a household has to pay 500 €/month for their heat supply. However, as can be seen is the TCO consist of tax approximately 20% of the costs. It may happen that taxes are not levied on hydrogen, or are less than the tax that is proposed in this analysis. Meaning that this cost component can be smaller or excluded in the cost structure of the TCO. With regard to the cost, deployment of hydrogen in a 'gallerijwoning' or 'flatwoning' with newer construction years are the least expensive options, however this is also caused by the fact that this type of building has a lower energy demand. Whether tax is part of the TCO does not influence the outcome. If an average is taken of the TCO of all houses, the average TCO is € 88,075, which is far higher than the average for all-electric and use of heat networks.

With regard to the results of case II, the TCO is quite high for non-stacked buildings, which matches the outcome of the results of case I. However, due to the energy saving package, the differences in TCO

between different construction years are substantially lower. In addition, hydrogen heating systems are at cheapest stacked buildings. Remarkable is that the TCO of a 'gallerijwoning' built between 1965 and 1974 the TCO is approximately 500 €/year higher. This is due to high investment costs of insulation for this type of house, where energy saving is relatively low.
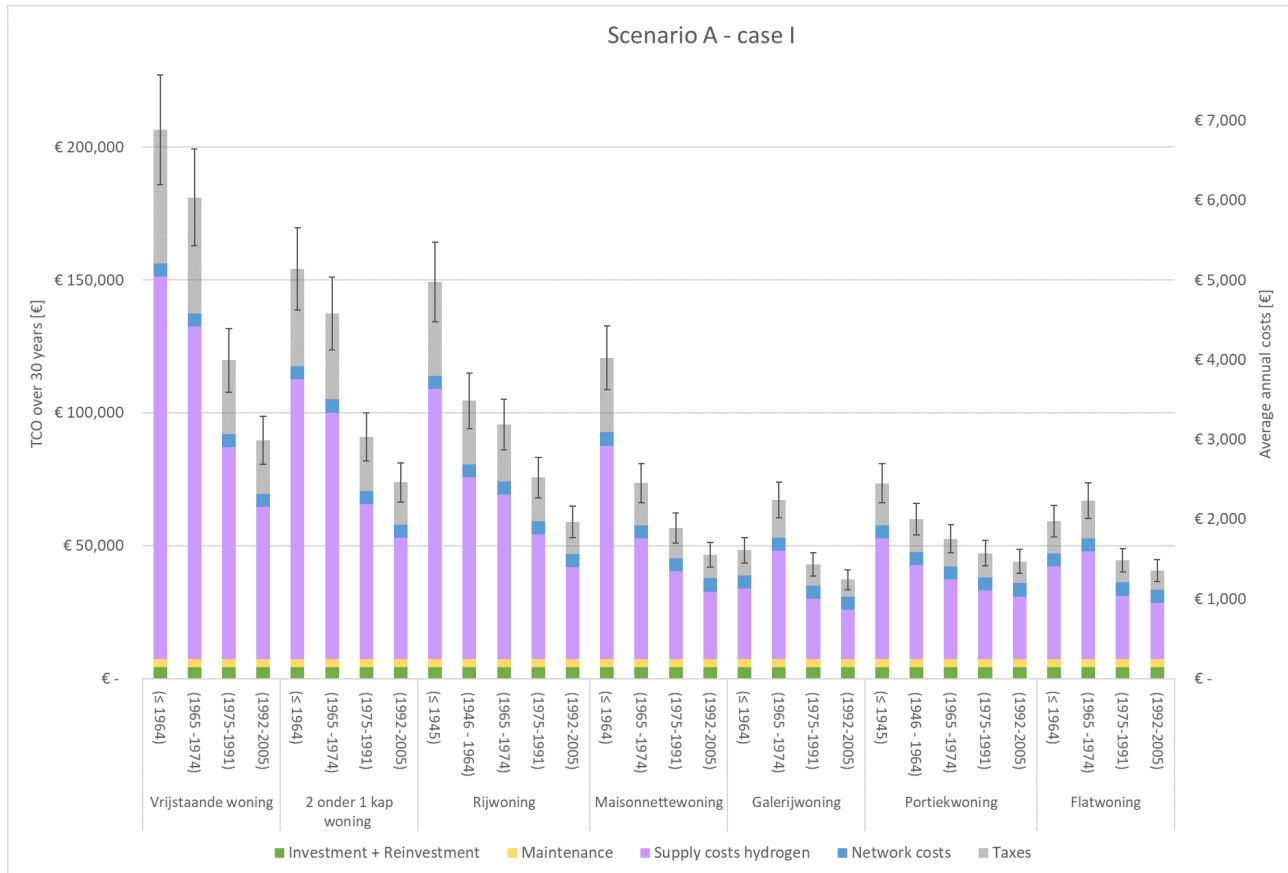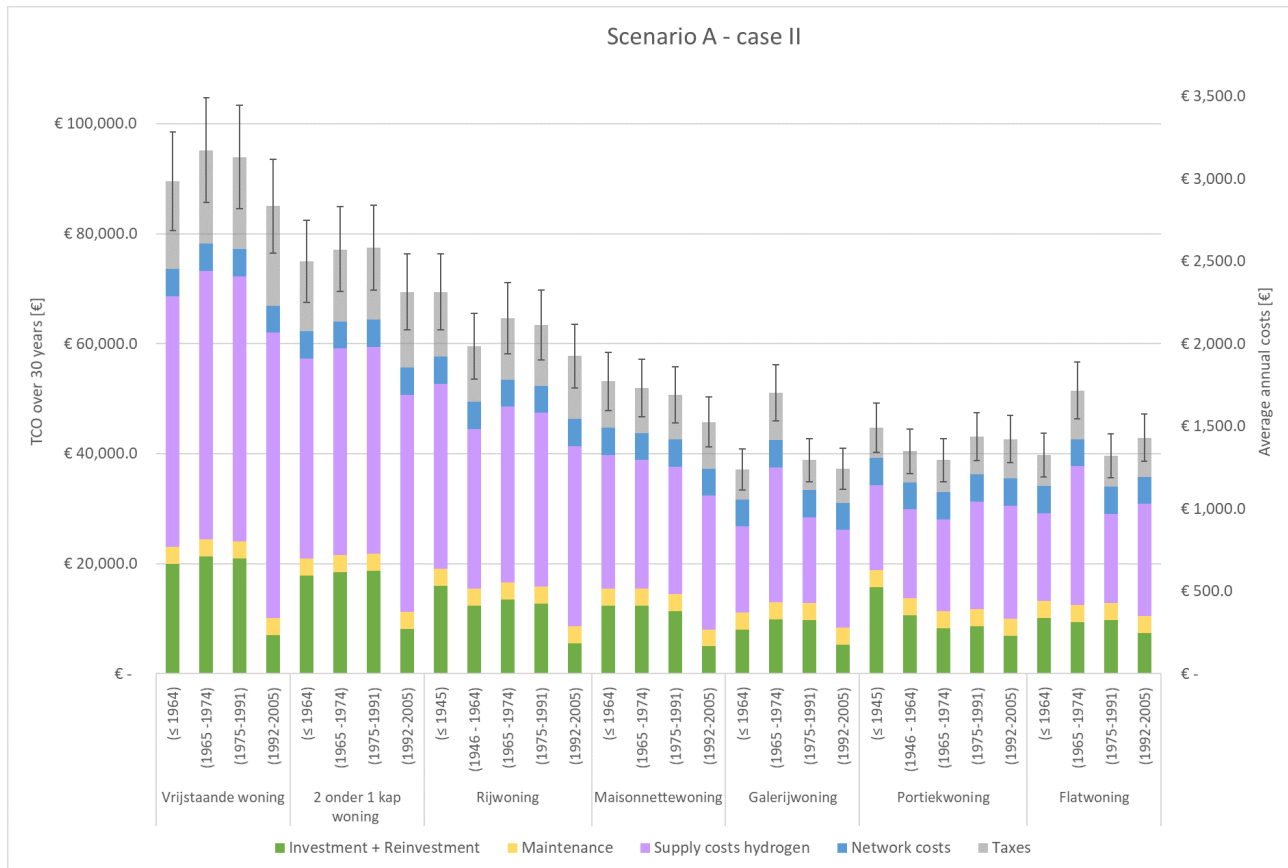

Figure 5.3: TCO over 30 years and the average annual costs for case II of scenario A presented per building. The costs are divided into four cost components, namely: (I) investment and reinvestment, (II) energy costs which contains supply costs and network costs, (III) taxes and (IV) maintenance costs. If taxes are not applied to hydrogen, this cost component can be excluded. The error bars represent an error margin of 10%.

When comparing both cases it can be concluded that, despite the high investment cost for insulation, in almost all type of buildings the advantage of energy saving outweighs the investment costs. However, this does not apply for 'gallerijwoning' and 'flatwoning' with construction years between 1992 and 2005. This is caused by the high hydrogen supply costs, which positively affects return on investment for insulation. This outcome disproves the impression that hydrogen is the cheap and easy natural gas-free alternative. As also from an economic perspective, insulation is the cheaper option. However, this outcome is extremely sensitive to the cost of hydrogen production as in both cases energy costs are the largest cost item. The average TCO of case II is equal to € 59,698, which is higher than the average of the alternatives.

5.3.2   Scenario B - Hydrogen from the Netherlands by 2030

In case it still takes a decade before hydrogen can be supplied to the built environment, this scenario examines a switch to a hydrogen heating system by 2030. As the technologies and hydrogen production is more mature by then, lower hydrogen production and hydrogen boiler costs are assumed. Investment of the hydrogen boiler is expected to be € 1,955 (linear to the proposed price drop of scenario A for the reinvestment) and a reinvestment of € 1,759 (price drop of 10% compared to investment price). The expected hydrogen production price is 2.92 €/kg (0.0876 €/kWh) by 2030 [40]. To determine the price drop to 2060, the same exponential factor is applied as in scenario A, namely 0.976^{2030-T}.

Figure 5.4: TCO over 30 years for the 30 types of buildings for case I of scenario B where hydrogen supply price is set at 2.92 €/kg. The costs are divided into four cost components, namely: (I) investment and reinvestment, (II) energy costs which contains supply costs and network costs, (III) taxes and (IV) maintenance costs. If taxes are not applied to hydrogen, this cost component can be excluded. The error bars represent an error margin of 10%.

The TCOs for scenario B case I and II are presented in Figures 5.4 and 5.5. Comparing case I of scenario A with B, it can be concluded that the costs for a hydrogen system drops approximately 25 %, where for case II costs decrease with 20%. Identical to scenario A, only 'gallerijwoning' and 'flatwoning' built between 1992 and 2005 are cheaper for case I than case II. However, the differences in costs are much smaller than in scenario A. In general, the energy supply costs are still relatively high, as the average TCO for all buildings is for case I is €64,926 and for case II is € 47,365. This is in both cases more expensive than connecting to a heat network, which indicates that hydrogen heating systems are probably not the cheapest alternative

for natural gas-free heating by 2030 as well. However, the average TC is more close to the alternatives in this scenario, which indicates that at a hydrogen production cost of 2,92 €/kg is probably near the tipping point to be competitive.

Figure 5.5: TCO over 30 years for the 30 types of buildings for case II of scenario B where hydrogen supply price is set at 2.92 €/kg. The costs are divided into four cost components, namely (I) investment and reinvestment, (II) energy costs which contains supply costs and network costs, (III) taxes and (IV) maintenance costs. If taxes are not applied to hydrogen, this cost component can be excluded. The error bars represent an error margin of 10%.

5.3.3   Scenario C - Hydrogen from the Sahara by 2020

This price scenario assumes hydrogen import from the Sahara for 1 €/kg (0.0300 €/kWh). In this case, year 2020 is used as base year, where the same parameters are used as in scenario A. Except the hydrogen production price is changed to 1 €/kg (0.0300 €/kWh) and it is assumed that the price remains equal over 30 years. As a result, the TCO of case I is on average decreased by 44% compared to scenario A case I. In addition, for 9 buildings it appears to be cheaper to apply case I than case II. This applies to the following houses: '2 onder 1 kap (1975-1991)', 'rijwoning (1992-2005)', ' maisonettewoning (1975-1991)', 'gallerijwoning (1975-1991) and (1992-2005)', 'portiekwoning (1975-1991) and (1992-2005)' and 'flatwoning (1975-1991) and (1992-2005)'. The hydrogen supply costs are too low to get a return on investment of insulation. However, for the other 20 types it is still more cost-effective to insulate the house, even with a hydrogen price of 1 €/kg. In case that taxes are not levied on hydrogen it will be cheaper to apply case I than case II for even more buildings, as taxes are a larger cost item in case I.
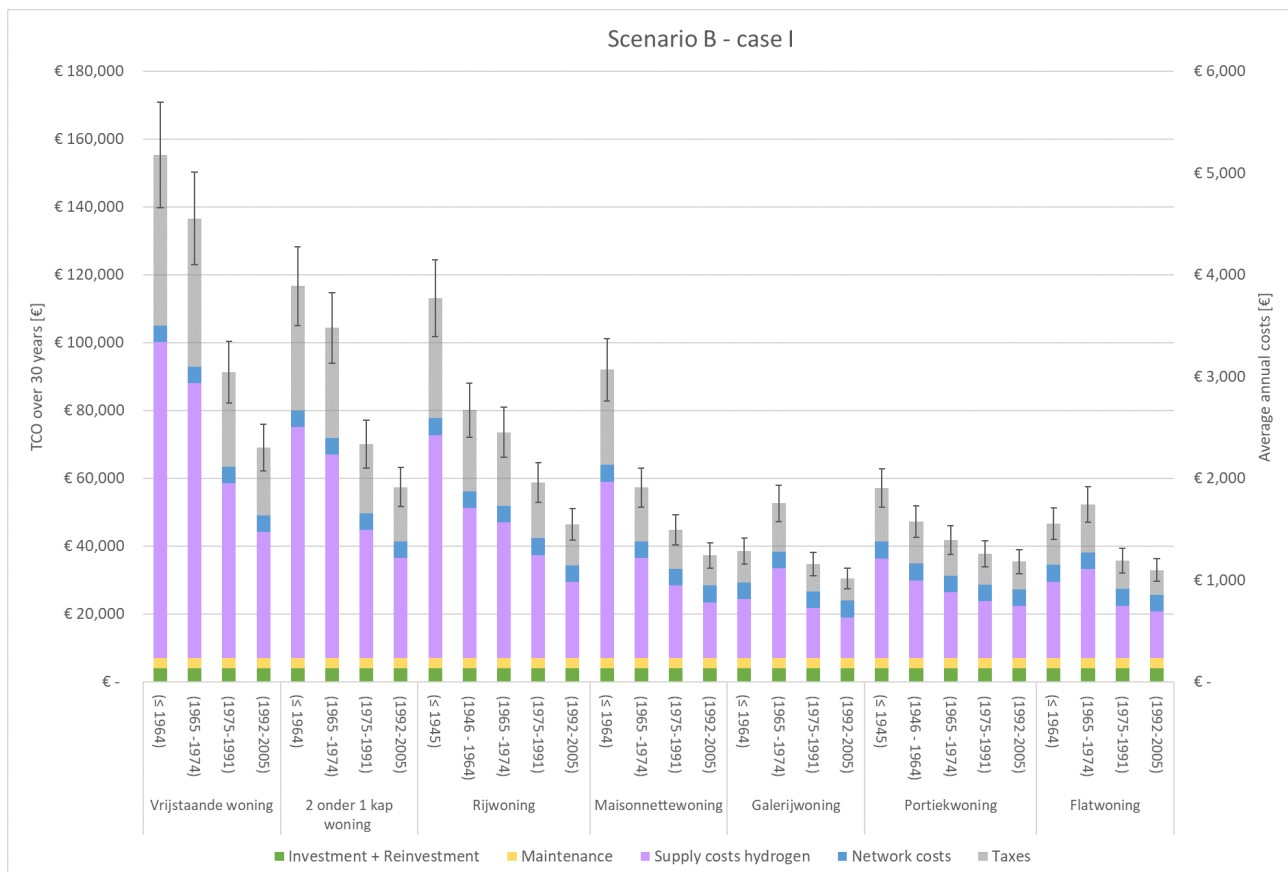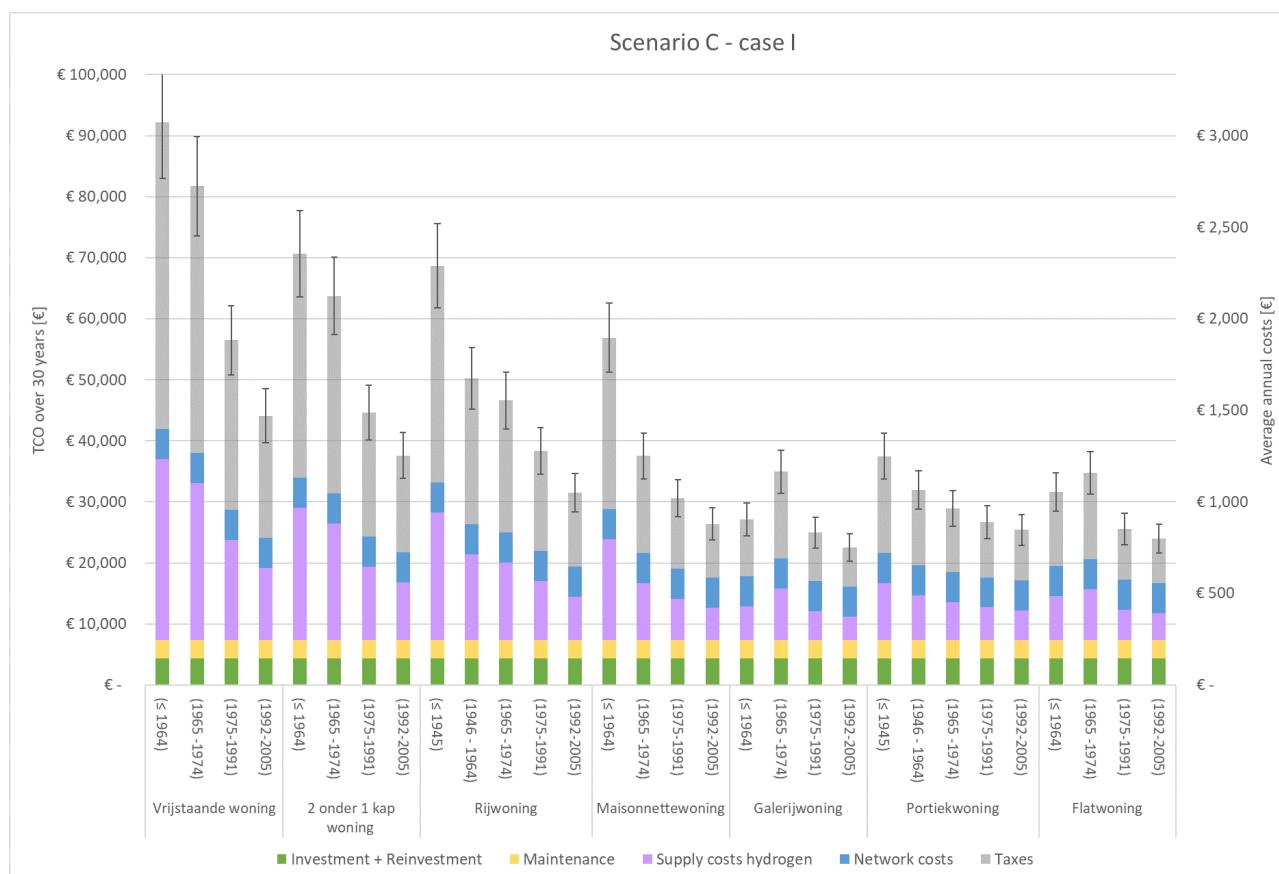
Figure 5.6: TCO over 30 years for the 30 types of buildings for case I of scenario C where hydrogen supply price is set at 1.0 €/kg. The costs are divided into four cost components, namely (I) investment and reinvestment, (II) energy costs which contains supply costs and network costs, (III) taxes and (IV) maintenance costs. If taxes are not applied to hydrogen, this cost component can be excluded. The error bars represent an error margin of 10%.

The average TCO of all buildings in case I is €47,422, where case II has an average TCO of €38,290. This price scenario states that hydrogen heating systems are competitive with alternative gas-free options. The allocation of taxes (∼ 44%), network costs (∼ 13%) and supply cost (∼ 43%) on the natural gas bill can be seen as standard. In Figure 5.6 tax is the largest cost item, which indicates that the hydrogen supply costs are in this scenario cheaper than natural gas. Table B.4 of Appendix B provides an overview of all calculated TCOs. The assumptions and costs used to perform the economic analysis are presented in Appendix B Table B.1 - B.3.
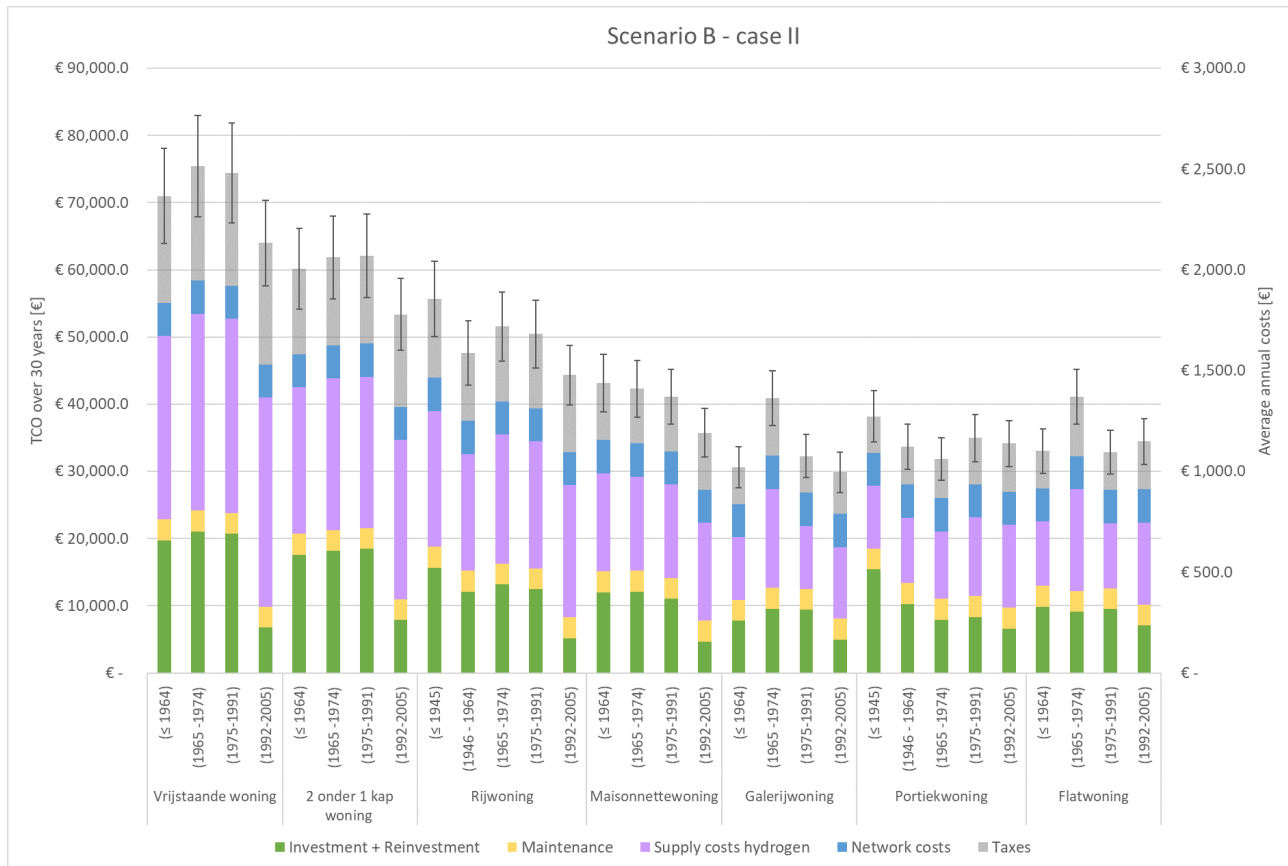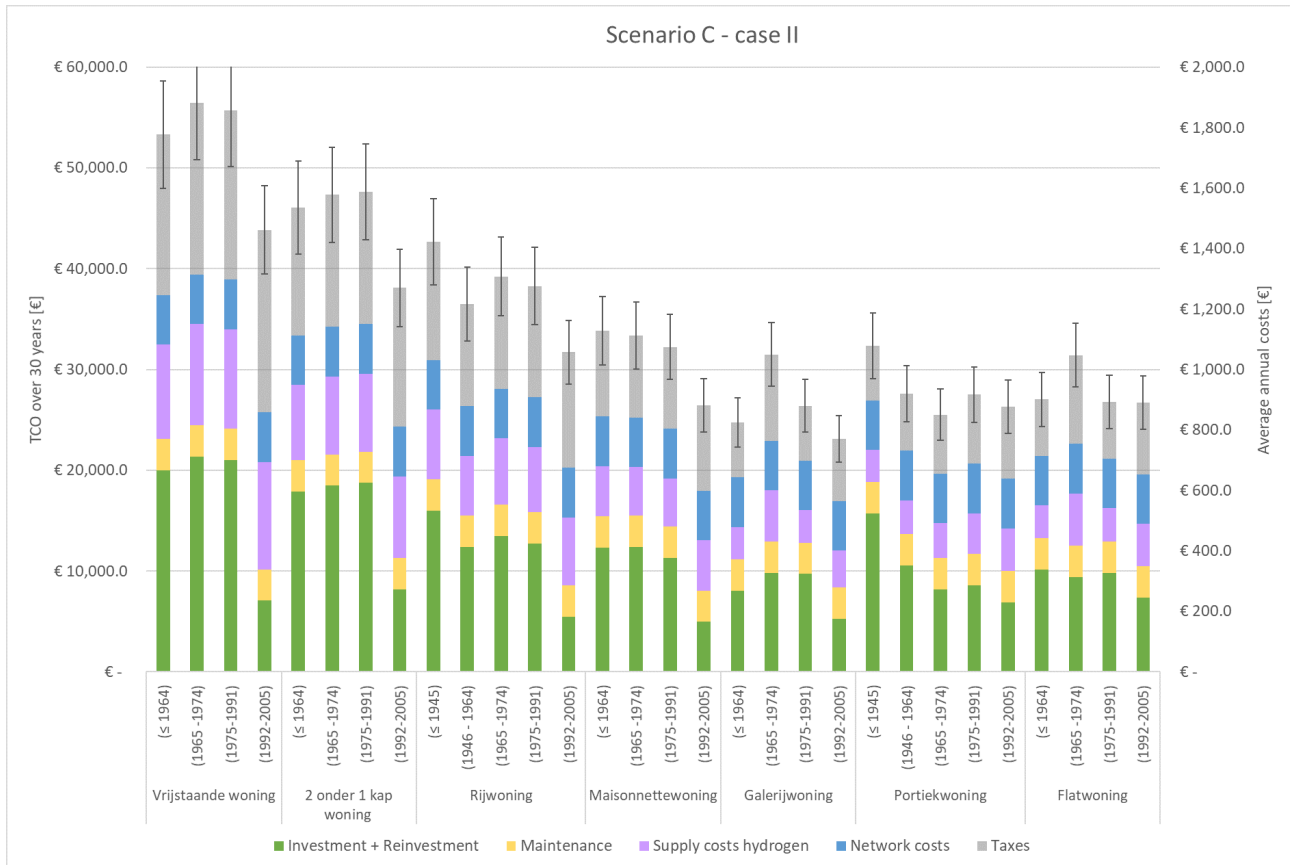
Figure 5.7: TCO over 30 years for the 30 types of buildings for case II of scenario C where hydrogen supply price is set at 1.0 €/kg. The costs are divided into four cost components, namely (I) investment and reinvestment, (II) energy costs which contains supply costs and network costs, (III) taxes and (IV) maintenance costs. If taxes are not applied to hydrogen, this cost component can be excluded. The error bars represent an error margin of 10%.

Chapter 6

Discussion

Some insightful results have been obtained from this study. Although hydrogen in general shows high potential in the energy sector, it appears not to reach its full benefit in the built environment for at least a decade. Due to time constrains a number of assumptions are made during the research, which could be further investigated in a follow-up research. The following remarks are relevant for the interpretation of the results.

Firstly, the amount of hydrogen available for the built environment is determined based on the quantities of renewable electricity needed for the current hydrogen demand of sectors that have no alternatives for hydrogen. In the above mentioned calculation presents a positive scenario which assumes (I) upper values of electrolyser, transport efficiencies and (II) demand response is operated by the chemical industry. This implies that no storage technology is required and subsequently, the outcome of the required of sustainable electricity amount is at lower limit for this analysis. Even in the most positive case, the analysis of the chemical industry already indicates that it will be quite a task to achieve this by using Dutch renewable electricity. The task will become even larger if this scenario is less attractive, where storage in that case is still required for the hydrogen production for the chemical industry or efficiencies turn out to be less due to lower system loads. Thereby, deployment of hydrogen in sectors that currently make use of fossil fuels (e.g. as the industry and transport) have precedence over the built environment, whereas they have access to fewer energy alternative for natural gas in comparison with the built environment.

Secondly, it is assumed that energy demand of the built environment remains stable from 2018 to 2030 in the calculations of renewable electricity needed for hydrogen production. This assumption was made because hydrogen use in the built environment is considered as the natural gas-free alternative for which insulation is not strictly necessary. However, if energy saving measures are applied in the built environment, the heat demand will decrease. Though this will not make any difference to the fact that there is no room for hydrogen production for the built environment in the Dutch government plans for sustainable electricity production. Nonetheless, if the Dutch government eventually wants to import sustainable electricity or hydrogen from other countries, the use of hydrogen by other sectors can be increased.

Thirdly, the TCO is extremely sensitive to the hydrogen supply costs. As Dutch green hydrogen is not commercially available yet, numerous assumptions had to be made with regards to the future pricing structure. In this study, it is assumed that cost components as taxes, network costs and supply costs will be part of the hydrogen bill. It can be guaranteed that supply and network costs are part of the hydrogen

bill, however it is still uncertain if taxes will be levied. Nonetheless, the results are presented in such a way that this part of the TCO can easily be excluded. Furthermore, due to this price uncertainty the TCO is performed for 3 scenarios and therefore gives a range of results which incorporate this uncertainty.

Lastly, the TCOs of different buildings can not be compared with each other. The TCO calculation is based on the energy performance and building characteristics and is not standardised by floor area or volume etc. of the building.

The obtained results show that at this moment in time hydrogen heating systems using Dutch green hydrogen are not a realistic alternative. However, if hydrogen production costs do drop significantly in the near future, the TCO will be competitive with the current alternative options for natural gas-free heating in the built environment.

Recommendations Based on the obtained results, a number of recommendations are proposed. This paragraph discusses the considered recommendations for DWA, follow-up research and policy advice.

Although DWA nowadays has a main focus on heat supply by heat networks or all electric solutions, it remains important to stay up to date on the development of renewable energy technologies and to monitor the price development of green hydrogen. If the price of hydrogen drops below 2.92 €/kg, in that case there could possibly be a positive economic case for the deployment of a hydrogen heating system.

In addition, this study indicated that a wind profile matches better with the heat demand of the built environment in contrast to a solar panel profile. Currently, only solar panels are installed near homes, while heating systems that use electricity could make better use of renewable electricity generated by wind power. This outcome encourages to conduct research on wind energy generation near homes.

With regard to government policies, this study recommends to take the available amount of renewable electricity into consideration when providing financial support for installation of electrolysers, and thus hydrogen production. Hydrogen production by electrolysers have high efficiency losses, which in the case of grey electricity use result in more CO_2 emissions. It is therefore important that hydrogen is produced in a sustainable way, as the aim of the government is to reduce CO_2 emissions. It is recommended that the Dutch government extents the current plans for sustainable electricity generation with alternative solutions if the Netherlands aims to be independent in their energy supply. The current plans are a step in the right direction, but are unfortunately nowhere near the extent necessary.

Chapter 7

Conclusion

This research aims to determine the possible role of hydrogen in the heat supply of the Dutch built environment. It analyses to what extent it is feasible to substitute the current natural gas use of the built environment by Dutch green hydrogen and the required landscape or space needed for renewable electricity production. Furthermore, it indicates how much hydrogen is used today and how much area for renewable electricity production is needed to make these quantities of hydrogen sustainable. After that, an economic assessment is performed for which a Total Cost of Ownership is calculated for 30 buildings, which together reflect the total Dutch housing stock. Three different price scenarios are proposed, namely: (A) Hydrogen from the Netherlands by 2020, (B) Hydrogen from the Netherlands by 2030 and (C) Hydrogen from the Sahara by 2020. For each scenario 2 cases are executed: case (I) hydrogen heating system in the current status of the building and case (II) a hydrogen heating system in combination with insulation. Based on the obtained results, the cost-effectiveness of the deployment of hydrogen for the built environment is assessed.

The chemical industry currently uses 163 PJ of grey hydrogen. In the near future, this production process needs to be transformed to a sustainable process, as there is no other sustainable alternative available for hydrogen in this sector. According to the results of Chapter 4 an annual renewable electricity generation of 200 PJ is needed by 2030 to supply the required amount of hydrogen to the chemical industry. This amount of renewable electricity can be produced by 371 km^2 of solar panels, or 74% of the total expected installed capacity onshore and offshore wind turbines by 2030. The Dutch built environment consumes 408 PJ of natural gas for heat supply. To supply the same amount of energy by use of hydrogen, 530 PJ of renewable electricity needs to be generated per year. In terms of size, an additional 686 km^2 of surface is needed for solar panels and 2 times the total expected installed capacity of onshore and offshore wind turbines by 2030. Based on the results mentioned above, it can be concluded that it is already quite a challenge to produce sustainable hydrogen for the chemical industry. Certainly until 2030, the plans for sustainable electricity production in the Netherlands does not allow the production of hydrogen for the built environment.

In this paragraph the main results of the economic assessment are highlighted. The average TCO of scenario A case I is € 88,075 and for case II € 59,698. Both cases the TCOs are higher than alternative gas free options, which indicates that the deployment of a hydrogen heating system is not a cost-effective step by 2020. However, the average TCO of case II is in all performed scenarios lower than case I, which indicates that even in a low price scenario, insulation costs can be returned in most of the analysed homes. Scenario B has for case I an average TCO of € 64,926 and for case II is € 47,365. This price scenario assumes the

application of a hydrogen heating system by 2030, with a hydrogen price of 2.92 €/kg (0.0876 €/kWh) and lower costs of investment for the hydrogen boiler. However, the calculated TCOs are even for this scenario are rather high compared to alternative options for gas free heating. However, the average TCO of this scenario is almost competitive with the alternatives, which indicates that a hydrogen price of 2.92 €/kg is near the tipping point. Scenario C seems to be the affordable option, however whether hydrogen will ever become available for these costs is still questionable. The deployment of a hydrogen heating system is the most convenient in buildings where insulation costs are not being returned by the benefit of energy saving. For all 3 scenarios this applies to 'gallerijwoning' and 'flatwoning'with a construction year between 1991 -2005, as case II had a higher TCO than case I.

In general, it can be said that the role of hydrogen in the heat supply of the built environment will certainly be small in the coming decade. This because there is not sufficient renewable electricity available for the production of green hydrogen and the costs are still far too high to be competitive with alternative gas free options. Nevertheless, if hydrogen production price drops below 2.92 €/kg this may change.

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Appendix A

Input data - Results A

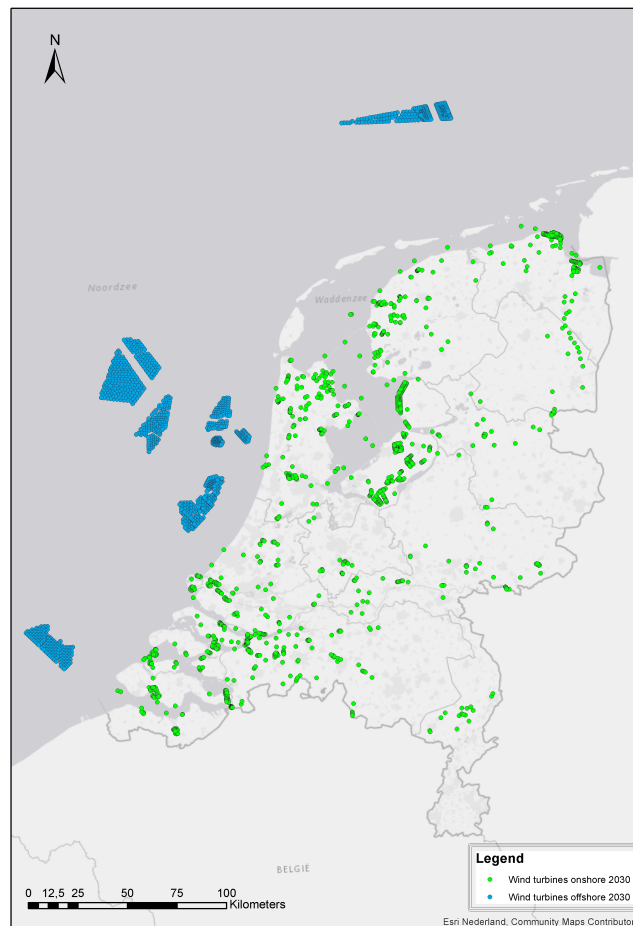## A.1 Locations on and offshore wind turbines

Figure A.1: Geographical locations of the on and offshore wind turbines which are expected to be installed by 2030 if a regional strategy is followed. The total capacity onshore is 8 GW and offshore 10.5 GW.

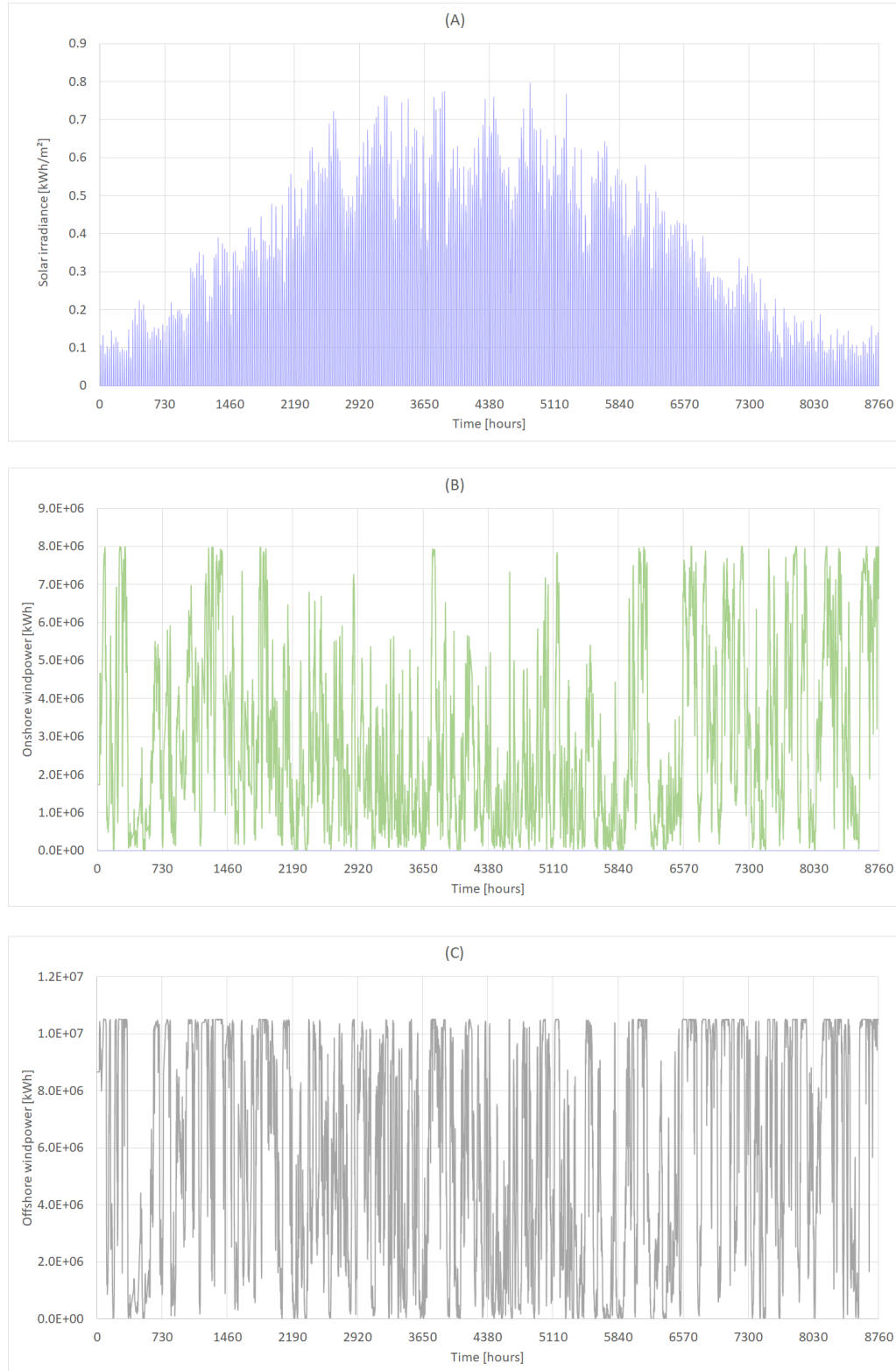## A.2 Solar irradiance and wind power profiles

Figure A.2: Used profiles to determine the standardised profiles, with (A) Solar irradiance profile which is determined based on the average solar irradiance between 2015-2019, (B) modelled onshore wind turbine power profile and (C) modelled offshore wind turbine power profile. The wind power profiles are both based on the wind turbines shown in Figure A.1

A.3   Technological and economic parameters

A.3.1   Electrolyser technologies

Table A.1: Technological and economic parameters of hydrogen production technologies

|	AEC	PEMEC	SOEC
Efficiency (%)	67 - 82 [21][43], 81 - 93 [23]	67 - 82 [21], 73 - 86 [23]	< 110 [21]
Operating temperature (°C)	70 - 90 [23], 60 - 80 [21]	60 - 80 [23], 50 - 80 [21]	700 - 900 [23], 650 - 1000 [21]
Operating pressure (bar)	20 - 30 [23]	30 - 60 [23][44], <200 [21]	< 25 [21][44]
Hydrogen purity (%)	99.5 [21]	99,99 [23][21]	99.9 [21]
Capacity range (kW)	1.8 - 5,300 [45]	0.2 - 1,150 [45]	170 - 840,000 [46]
Capital costs (€/kW$_{el}$)	1,000 - 1,200 [45],	1,900 - 2,300 [45]	5,500 [21]
Capital costs 2030 (€/kW$_{el}$)	370 - 800 [45]	250 - 1,270 [45]	1,200 - 2,500 [21], 500 - 1000 [43]
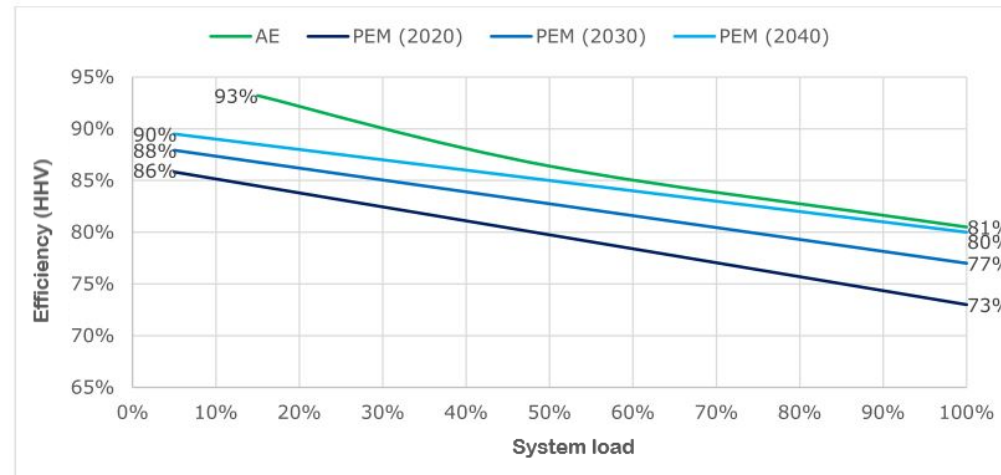
Figure A.3: The efficiency of Alkaline Electrolyser (AE), Polymere Exchange Membrane Electrolyser (PEM) plotted against the system load.

A.3.2 Storage technologies

Table A.2: Technological and economic parameters of hydrogen storage technologies

	Hydrogen tube/tanks	Salt caverns
Efficiency (%)	80 - 98 [13]	95 [24]
Operating pressure (bar)	200 - 350 [13]	80 - 180 [13]
Price (€/MWh)	7.69 [24]	2.97 [24]

A.3.3 Fuel cell technologies

Table A.3: Technological and economic parameters of residential fuel cell technologies

	AFC	PEMFC	SOFC
Capacity (kW)	10 - 100 [28]	0.75 - 250 [47][28]	0.75 - 3,000 [47][28]
Electrical efficiency (%)	60 [28]	35 - 39 [47]	45 - 60 [47]
Thermal efficiency (%)	20 [47]	55 [47]	30 - 45 [47]
Combined heat and power efficiency (%)	> 80 [28]	70 - 90 [28]	< 90 [28]
Operating temperature (°C)	90 - 100 [28]	50 - 100 [28]	600 - 1000 [28]
Capital costs (€/kW$_{el}$)	3,000 [48]	10,000 [28]	20,000 [28]

Appendix B

Input data - Results B

B.1 CAPEX

Table B.1: CAPEX presented per cost element, which are used to perform the TCO of the different scenarios

Investment	Value
Hydrogen boiler 2020	€ 2,094.21
Hydrogen boiler 2030	€ 1,954.60
Hydrogen boiler 2035	€ 1,884.79
Hydrogen boiler 2045	€ 1,759.14
Installation costs hydrogen boiler	10% of investment
Costs for adjusting the natural gas network	€ 205.45

B.1.1 Insulation costs

Table B.2: Cost for insulation per building element presented in € per m^2. Based on these costs the insulation costs per type of building is calculated.

Investment	Low-rise buildings	High-rise buildings
Ground floor	20.00 €/m^2	20.00 €/m^2
Flat roof	193.00 €/m^2	193.00 €/m^2
Sloping roof	53.00 €/m^2	53.00 €/m^2
Facade	21.00 €/m^2	19.00 €/m^2
Single glazing to HR++ glazing	139.00 €/m^2	160.00 €/m^2
Double glazing to HR++ glazing	142.00 €/m^2	164.00 €/m^2

B.2 OPEX

Table B.3: OPEX presented per cost element, which are used to perform the TCO of the different scenarios. *hydrogen supply costs are hydrogen production costs plus charges for transport and profit

Investment	Value
Hydrogen production costs 2020	0.1460 €/kWh
Hydrogen production costs 2030	0.1141 €/kWh
Charges for transport and profit hydrogen supply	20 % of hydrogen supply costs
EB	0.0341 €/kWh
ODE	0.0079 €/kWh
Network costs	190.36 €/year
Maintenance costs hydrogen boiler	120.00 €/year

B.3 TCO over 30 years per scenario

Table B.4: Overview of the TCO per type of building for each price scenario and case.

Type	A-I	A-II	B-I	B-II	C-I	C-II
Vrijstaande woning (≤1964)	€217,684	€92,981	€155,388	€73,082	€107,465	€58,128
Vrijstaande woning (1965-1974)	€190,729	€98,938	€136,574	€77,650	€94,977	€61,616
Vrijstaande woning (1975-1991)	€125,881	€97,655	€91,313	€76,642	€64,936	€60,822
Vrijstaande woning (1992-2005)	€94,022	€88,978	€69,076	€66,379	€50,176	€49,326
2 onder 1 kap woning (≤1964)	€162,212	€77,752	€116,670	€61,813	€81,766	€49,936
2 onder 1 kap woning (1965-1974)	€144,546	€80,031	€104,340	€63,581	€73,582	€51,306
2 onder 1 kap woning (1975-1991)	€95,454	€80,333	€70,076	€63,869	€50,840	€51,584
2 onder 1 kap woning (1992-2005)	€77,311	€72,463	€57,412	€55,186	€42,435	€42,270
Rijwoning (≤1945)	€157,177	€72,018	€113,156	€57,232	€79,434	€46,251
Rijwoning (1946-1964)	€109,821	€61,777	€80,104	€48,997	€57,496	€39,575
Rijwoning (1965-1974)	€100,446	€67,087	€73,560	€53,036	€53,152	€42,625
Rijwoning (1975-1991)	€79,264	€65,783	€58,776	€51,902	€43,340	€41,624
Rijwoning (1992-2005)	€61,598	€60,273	€46,445	€45,868	€35,156	€35,182
Maisonettewoning (≤1964)	€126,880	€55,023	€92,010	€44,262	€65,398	€36,408
Maisonettewoning (1965-1974)	€77,137	€53,724	€57,291	€43,382	€42,354	€35,855
Maisonettewoning (1975-1991)	€59,254	€52,480	€44,809	€42,191	€34,070	€34,704
Maisonettewoning (1992-2005)	€48,489	€47,628	€37,296	€36,881	€29,083	€29,037
Gallerijwoning (≤1964)	€50,312	€38,349	€38,568	€31,337	€29,927	€26,397
Gallerijwoning (1965-1974)	€70,453	€52,900	€52,626	€42,034	€39,258	€34,099
Gallerijwoning (1975-1991)	€44,757	€40,013	€34,691	€33,001	€27,354	€28,061
Gallerijwoning (1992-2005)	€38,636	€38,607	€30,419	€30,678	€24,518	€25,025
Portiekwoning (≤1945)	€76,963	€45,870	€57,170	€38,897	€42,274	€33,988
Portiekwoning (1946-1964)	€62,770	€41,707	€47,263	€34,447	€35,698	€29,313
Portiekwoning (1965-1974)	€54,913	€40,105	€41,780	€32,608	€32,059	€27,291
Portiekwoning (1975-1991)	€49,184	€44,595	€37,781	€35,866	€29,405	€29,591
Portiekwoning (1992-2005)	€45,929	€44,220	€35,509	€35,085	€27,897	€28,495
Flatwoning (≤1964)	€61,815	€40,954	€46,597	€33,785	€35,256	€28,723
Flatwoning (1965-1974)	€70,019	€53,415	€52,323	€42,261	€39,057	€34,101
Flatwoning (1975-1991)	€46,276	€40,841	€35,751	€33,606	€28,057	€28,493
Flatwoning (1992-2005)	€42,326	€44,450	€32,994	€35,393	€26,228	€28,864
Average	€88,075	€59,698	€64,926	€47,365	€47,422	€38,290