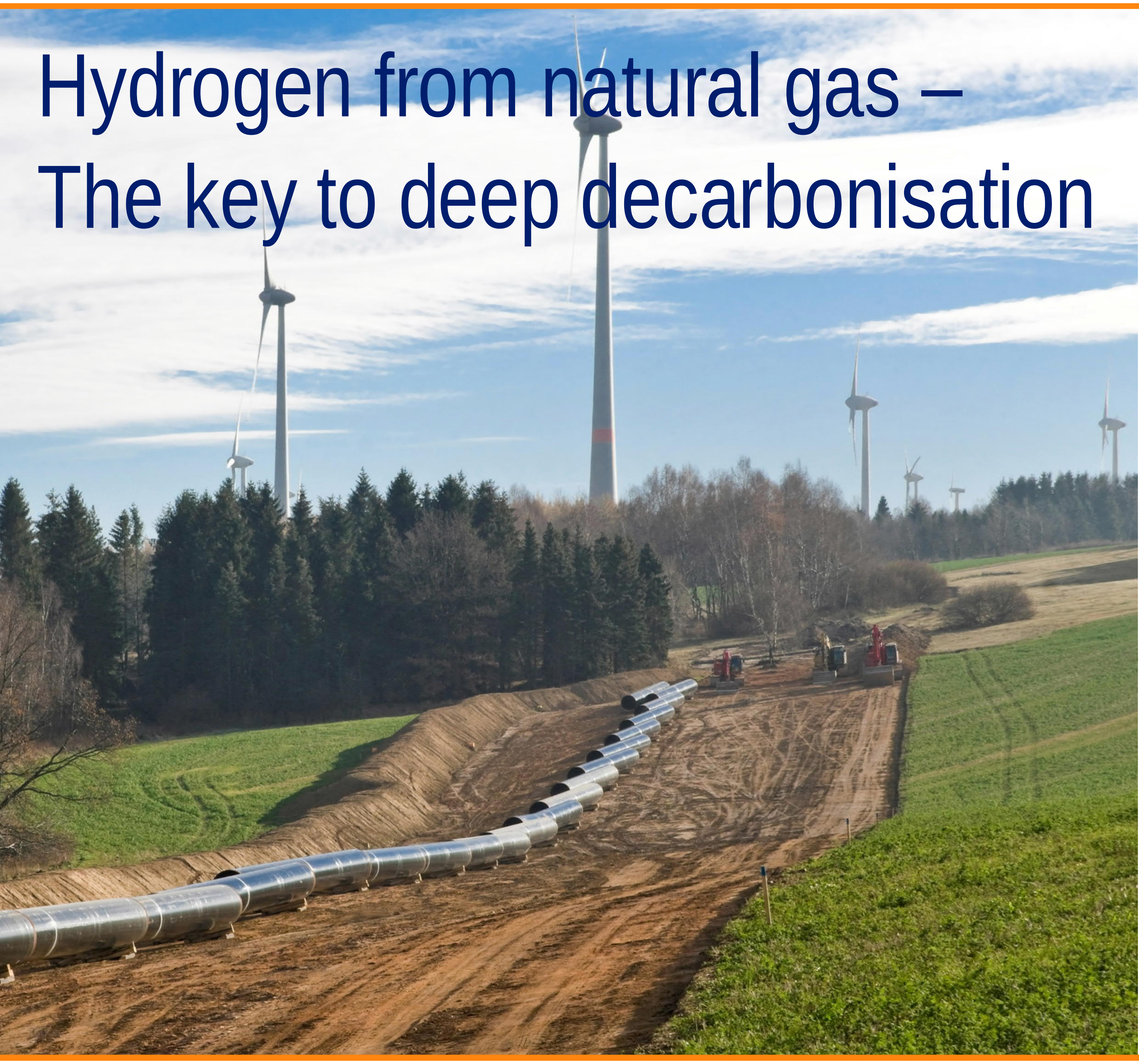
Discussion Paper commissioned by Zukunft ERDGAS – July 2019

Hydrogen from natural gas – The key to deep decarbonisation



Pöyry Management Consulting

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EXECUTIVE SUMMARY

Background and purpose

This Discussion Paper was commissioned by Zukunft ERDGAS to contribute to the debate concerning the deep decarbonisation of the European energy sector required to meet the Paris Agreement targets.

Previous discussion papers have put forward decarbonisation pathways that rely heavily on 'All-Electric' solutions. These depend predominantly on renewable electricity to deliver decarbonisation of all sectors. This paper offers an alternative to an 'All-Electric' solution by building an alternative pathway that allows the inclusion of gas based technologies alongside the 'All-Electric' pathway technologies. The new pathway demonstrates that hydrogen from natural gas can be an essential complement to renewable electricity. The pathway also considers the benefits of utilising methane pyrolysis technology in Europe to produce zero carbon hydrogen.

Decarbonising the energy sector

Awareness of climate change impacts and the need for deep decarbonisation has increased greatly in recent years. In response to this growing awareness and the urgency of decarbonisation, policy makers have taken action and in 2015 agreed to what is known as the Paris agreement. This has set the target to limit the expected global average temperature increase to significantly less than 2°C, with the ambition to keep to the limit to less than 1.5°C.

In order to achieve such necessary and ambitious targets, the European economy, and in particular the energy sector, needs to significantly reduce CO_2 emissions to a fraction of current levels (e.g. -80%, -95%) with a growing consensus that net zero emissions will be required. Many changes will be required in how we work, travel, heat our homes and how we obtain the energy necessary to carry out all these activities.

From the 1990 baseline of 5,751MtCO_2, a 24% reduction in CO_2 emissions had been achieved by 2016 across Europe (EU28 plus Norway and Switzerland)[1]. Limiting the temperature increase to <1.5°C by 2050 will require a reduction of emissions by another three times the amount already achieved.

In 2018 the EU published its vision for the future of energy in Europe 'A Clean Planet for All'[2] which aims at creating a "prosperous, modern, competitive and climate neutral economy by 2050." A set of pathways has been developed and assessed that rely heavily on renewable energy and energy efficiency, with a limited role for natural gas and hydrogen.

Different pathways to decarbonisation

In order to investigate alternative decarbonisation scenarios, Pöyry uses a pathway approach, imagining and modelling different possible futures for the European energy system and analysing the implications and risks from choosing a certain path. A pathway is defined by the constraints that are placed on certain technologies that can contribute to decarbonisation. By keeping the underlying assumptions, such as the development of demand, technology developments and commodity costs consistent between the pathways, we are able to see the impacts of varying the constraints. The analysis in this paper builds on Pöyry's 'Full Energy-Sector Decarbonisation Study'[3], which compared an 'All-Electric' pathway with a more balanced 'Zero Carbon Gas' pathway.

In the 'All-Electric' pathway, decarbonisation was mainly achieved through restricting options to electrification, and no hydrogen or other zero carbon or decarbonised gas was allowed. The 'Zero Carbon Gas' pathway, on the other hand, allowed various forms of 'zero carbon gas' to contribute on an economic basis. This pathway showed a reduction in delivery risks and costs compared to the 'All-Electric' pathway.

In this study, a 'Zero Carbon Hydrogen' pathway has been developed, which uses identical assumptions to the 'Zero Carbon Gas' pathway, with the addition of pyrolysis as an available technology to produce hydrogen alongside electrolysis and steam methane reformation with carbon capture and storage (CCS).

1 Throughout this report, results are based on Europe defined as EU 28 plus Norway and Switzerland unless otherwise stated.

2 European Commission. "A Clean Planet for all. A European strategic long-term vision for a prosperous, modern, competitive and climate neutral economy." 2018.

3 Pöyry Management Consulting. "Fully decarbonising Europe's Energy system by 2050." 2018.

Study summary messages and conclusions

Renewables will play a significant role in all pathways as a cost-effective form of clean energy in the future. In the 'Zero Carbon Hydrogen' pathway, renewables dominate in the power sector, and passenger vehicles and non-process heat sectors are electrified.

Relying on very high levels of electrification in an 'All-Electric' future is a high risk strategy. EU targets are more likely to be achieved if hydrogen from natural gas is included in the solution. The 'All-Electric' pathway relies on new nuclear, fast grid reinforcement and a solution to the inherent lack of seasonal storage. It also risks failing to decarbonise sectors that cannot easily be electrified raising the real possibility that overall decarbonisation targets may be missed.

Zero carbon hydrogen produced from natural gas can significantly reduce these risks when used as part of the energy mix. It can therefore be an **essential** complement to renewables for the successful deep decarbonisation of the European economy. Hydrogen makes a significant contribution to the heavy transport and process heat sectors and allows non-process heat to decarbonise where electrification is not feasible.

Development of pyrolysis will allow cost-effective, practical and secure development of hydrogen at scale and foster competition in the energy sector. Pyrolysis has key advantages – it is cheaper and more scalable than electrolysis and overcomes many of the barriers associated with widespread deployment of CCS (which would be necessary for SMR to produce zero carbon hydrogen).

Hydrogen reduces the risks of missing decarbonisation targets

The 'Zero carbon Hydrogen' pathway reduces the risk that Europe fails to meet its decarbonisation goals. It could also result in lower costs and minimise disruption for residential and industrial users. Analysis shows that there are several prerequisites of an 'All-Electric' pathway that, if not met, would jeopardise meeting decarbonisation targets. Allowing hydrogen to play a role will significantly reduce these risks. The following table presents the risks to decarbonisation and the impact on the different pathways that we have analysed.

Risk description	Risk in 'All-Electric'	Risk in 'Zero Carbon Gas'	Risk in 'Zero Carbon H_2'	Benefits of 'Zero Carbon Hydrogen' pathway
Electrification of heavy good vehicles is not technically feasible within timeframe	(X)	*none*	*none*	Hydrogen provides alternative in heavy transport
Biomass supply chain does not deliver the volumes needed for power and heat	(X)	*none*	*none*	Very limited use of biomass in transport, heat and power
Nuclear power faces greater than expected political opposition and is not deployed	(?)	*none*	*none*	No new nuclear power generation is needed to be across Europe
Nuclear power cannot be operated flexibly (e.g. turn off for several days)	(?)	($)	($)	Limited reliance on nuclear power, since no new plants built
Heat pumps fail in cold conditions before reaching the -15° design limit	(?)	($)	($)	Reduced reliance on heat pumps due to use of more stand-alone hydrogen boilers
Heat pump supply chains do not develop quickly enough	($)	($)	($)	
Energy efficiency in residential properties evolves slower than expected, making heat pumps impractical	($)	($)	($)	
Electricity grid reinforcement (incl. distribution, transmission, interconnection) cannot keep pace with demand and renewables growth	(?)	($)	($)	Exisiting gas grids and hydrogen use provide alternative energy source
CCS faces greater than expected political opposition and/or technical obstacles resulting in limited availability	*None*	(?)	($)	Methane pyrolysis offers a viable alternative as a method of providing energy (hydrogen)

(X) Risk of missing targets – no other option available
(?) Significant cost increase, risk of missing targets
($) Cost increase

Hydrogen has an essential role in the heat and transport sectors

Hydrogen provides a feasible and practical option for those sectors and applications that are very difficult, or impossible, to electrify. These include:

- **Industrial process heat.** Very high temperature process heat applications (e.g. glass production, plastics and rubber manufacturing) cannot be electrified and otherwise can only decarbonise with biomass or CCS. This, in turn, introduces supply chain, political, and technical issues;
- **Space heating.** Many buildings are unsuitable for the use of heat pumps (e.g. poor insulation, cold weather, no space for radiators or underfloor-heating, excessive disruption to homes or businesses);
- **Heavy road transport.** It is impractical to use very large batteries / overhead lines for the haulage sector;
- **Waterborne transport[4].** Electrification is not feasible due to long journeys and therefore extended periods between possible re-charging.

In order for hydrogen to play a role in these sectors it requires a scalable and low carbon production method that can only be achieved with the use of natural gas.

Pyrolysis can be a cost-effective and scalable solution to hydrogen production

This is the first European decarbonisation study to consider methane pyrolysis as a third hydrogen production method alongside steam methane reforming with CCS and electrolysis.

Steam methane reforming (SMR)[5] is a thermal process already used today. The process reacts methane (CH_4) with steam to produce hydrogen and CO_2. In order to be carbon-neutral, it needs to be combined with carbon capture and storage (CCS) of the CO_2 produced. The key advantage of this technology is that it is currently the most developed option, especially at scale, and as such presents the most cost-effective form of hydrogen production even with the addition of CCS. Drawback is the need for complex storage of CO_2, which is not available in all countries and faces political opposition in many countries.

Electrolysis is another existing technology that splits water (H_2O) into hydrogen and oxygen using electricity. The hydrogen produced can be only be considered zero carbon if the electricity used is itself zero carbon. The fact that there are no direct carbon emissions and no other by-products that need to be stored, make this option attractive, although there are questions around higher cost and scalability.

Pyrolysis is the decomposition of methane into hydrogen and solid carbon (C). A developing technology[6] it has the potential to play an important role in hydrogen production in the future. This is because the carbon is in solid rather than in gaseous form and therefore requires no complex storage in underground caverns, as is the case with CCS. Solid carbon can be used in existing industries, such as carbon black for tyres, in concrete for construction, or new uses such as graphene.

Utilising pyrolysis mitigates the risk that widespread CCS deployment may not be possible in those countries where political opposition or technical challenges exist[7].

'Zero Carbon Hydrogen' pathway insights

Our analysis for the 'Zero Carbon Hydrogen' pathway has identified the following key insights:

Heat pumps and hydrogen boilers decarbonise the space and water heating sector. Heat pumps are deployed where practical and account for 50% of heat capacity, with hydrogen boilers contributing 27%. Hydrogen makes up 49% of fuel used; biomethane and electricity both contribute around 14% each in 2050.

Post-combustion CCS gas[8] is used in process heating, where available, whereas in other countries hydrogen is deployed. CCS accounts for 18% of capacity in the segment, while hydrogen accounts for 56% in 2050.

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4 Waterborne transport has not been analysed in detail in this study, as it was considered out of scope.

5 Both steam methane reforming (SMR) and auto-thermal reforming (ATR) are potential processes of splitting methane into hydrogen and CO_2. For the purposes of this paper, we will use the term SMR, but no particular preference is indicated through this.

6 IEA. "The future of hydrogen report." 2019.

7 This study assumes that the availability of CCS in Europe is limited to Norway, UK, Belgium, Denmark, Ireland, Netherlands and Poland. Electrolysis and pyrolysis are available in all countries.

Light passenger transport is mostly electrified, due to the high efficiency of battery electric vehicles. However, larger vehicles are decarbonised using hydrogen, as longer journeys and heavier weight makes batteries impractical in this segment. Hydrogen accounts for 42% of all fuel used in transport (LDV and HDV sectors) in 2050.

Renewables (solar PV and wind) account for 76% of power capacity and 72% of power generation. As conventional thermal power plants are decommissioned, they are replaced by hydrogen and CCS power plants. No new nuclear plants are commissioned.

Hydrogen demand is primarily met through pyrolysis and steam methane reforming with CCS gas. Electrolysis deployment is limited because there are insufficient periods of low electricity priced periods normally associated with excess renewable generation, due to flexible demand side response, especially from electric vehicles. Pyrolysis is widely deployed in the countries where CCS is not available. Pyrolysis makes up 55% of hydrogen production, while SMR with CCS supplies 30%, and electrolysis 15% in 2050.

Policy makers' role in securing a hydrogen future

Policy must play a significant role in achieving decarbonisation. Specifically it must enable industries to make the investments and adaptations necessary in order to develop a hydrogen energy economy. Accordingly, European and national policy makers will need to recognise the importance of hydrogen from natural gas in decarbonisation efforts and consider the following.

Policies that support the role of hydrogen in decarbonisation efforts and allow different technologies (including zero carbon gas) to compete on an equal basis should be developed to achieve the most efficient outcome.

Targets for zero carbon gas in the European energy mix should be set (including renewable gas from bio-sources and decarbonised gas), in order for investment in zero carbon gas options to become attractive and for innovation to progress.

Research into implementation of hydrogen technologies should be supported. These include fuel cells, hydrogen based fuels and methane pyrolysis methods, as well as uses for end use carbon products.

Investments in energy networks should be considered based on the impact of the investment on decarbonisation. The role of hydrogen from natural gas and the role of existing gas networks in enabling decarbonisation should be recognised, and research into converting natural gas networks to hydrogen should be supported. This should include demonstration projects from proof of concept towards implementation. Policy makers should ensure a level playing field for investments in infrastructure to support decarbonisation, whether it be the expansion of electricity grids or the conversion of natural gas grids.

[8] The term 'CCS' as it relates to the power and heat sectors in this paper, always refers to post-combustion CCS with natural gas. When used in the context of hydrogen production, it refers to methane reforming with CCS.

1. INTRODUCTION – THE CHALLENGES OF DEEP DECARBONISATION

1.1 Introduction to this Discussion Paper

This Discussion Paper was commissioned by Zukunft Erdgas to contribute to the debate concerning the decarbonisation of the European energy sector to meet the Paris Agreement targets.

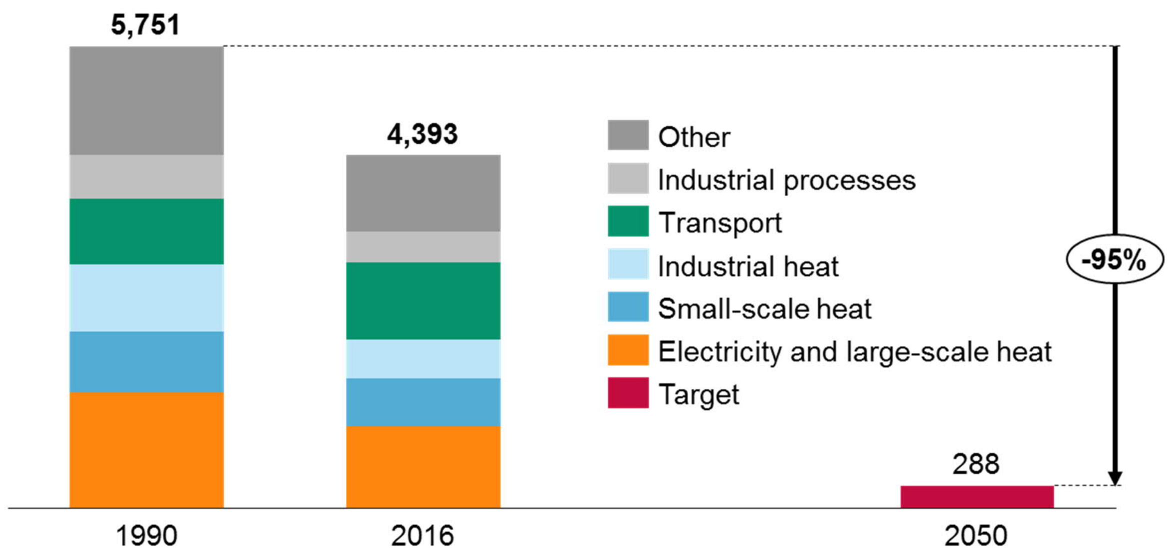
Previous discussion papers have put forward decarbonisation pathways that rely heavily on 'All-Electric' solutions[9]. These depend predominantly on renewable electricity to deliver decarbonisation of all sectors. This paper offers an alternative to an 'All-Electric' solution and demonstrates that zero carbon hydrogen from natural gas is an essential complement to renewable electricity. It also considers the benefits of utilising methane pyrolysis technology in Europe to produce zero carbon hydrogen.

1.2 Decarbonising the energy sector

Awareness of climate change impacts and the need for deep decarbonisation has increased greatly in recent years. In response to this growing awareness and the urgency of decarbonisation, policy makers have taken action and in 2015 agreed to what is known as the Paris agreement. This has set the target to limit the expected global average temperature increase to significantly less than 2°C, with the ambition to keep to the limit to less than 1.5°C.

In order to achieve such necessary and ambitious targets, the European economy, and in particular the energy sector, needs to significantly reduce CO_2 emissions to a fraction of current levels (e.g. -80%, -95%) with a growing consensus that net zero emissions will be required. Many changes will be required in how we work, travel, heat our homes and how we obtain the energy necessary to carry out all these activities, as shown in Figure 1.

Figure 1 – The scale of Europe's decarbonisation challenge – emissions by sector ($MtCO_2e$)



Source: 2016 National Inventory Submissions (Common Reporting Format) for EU, Norway and Switzerland
Note: Transport here refers to ground-based transport. Aviation and waterborne transport are counted towards the 'Other' segment

As evident from Figure 1, all of these sectors will need to contribute towards decarbonisation, since each one on their own currently exceeds the 2050 target for total emissions with a 95% economy-wide reduction

[9] Examples:
Eurelectric. "Decarbonisation Pathways." 2018
Wind Europe. "Breaking new ground. Wind Energy and the Electrification of Europe's Energy System." 2018.

compared to 1990. For some sectors, decarbonising will be more challenging. This study assumes that transport, heat (small-scale, large-scale, and industrial) and power will need to achieve a net zero emissions balance by 2050. This allows some other sectors such as agriculture and aviation to continue to emit some CO_2e within the 288 MtCO_2e limit. Meeting decarbonisation targets becomes more challenging if policy makers decide to aim for economy-wide 'net zero' emissions by 2050, not just the sectors covered in this study.

From the 1990 baseline of 5,751MtCO_2e, a 24% reduction in emissions had been achieved by 2016 across Europe (EU28 plus Norway and Switzerland)[10]. Limiting the temperature increase to <1.5°C by 2050 will require a reduction of emissions by another three times the amount already achieved.

In 2018 the EU published its vision for the future of energy in Europe 'A Clean Planet for All'[11] which aims at creating a "prosperous, modern, competitive and climate neutral economy by 2050." A set of pathways has been developed and assessed. These include a strong reliance on renewable energy and energy efficiency, but a limited role for natural gas and hydrogen.

1.3 Pathways to achieving decarbonisation

Pöyry uses a pathway approach, imagining and modelling different possible futures for the European energy system and analysing the implications and risks from choosing a certain path. A pathway is defined by the constraints that are placed on certain technologies that can contribute to decarbonisation. By keeping the underlying assumptions, such as demand, technology costs and commodity prices consistent between pathways, we are able to see the impacts of varying constraints.

While opinions differ greatly on how to achieve decarbonisation, common across the analysis in most studies is the belief or message that electricity from wind and solar PV will grow substantially. Renewables will therefore play a significant role in all pathways as a cost-effective form of clean energy in the future.

It appears that many stakeholders have in the past favoured an 'All-Electric' pathway to delivering a decarbonised energy system. Such a pathway relies on electrification of most of the heat and transport systems, and restricts the use of zero carbon gases, such as hydrogen or biomethane.

However, there are limits to what can be achieved with only electricity, as has been shown in our previous study, 'Fully Decarbonising Europe's Energy System by 2050[12]'. These include ensuring security of supply, both from a short-term, balancing perspective (managing the variability of wind and solar power), and from a seasonal perspective (for example, peak energy demand in winter is much higher than in the summer). Significant technological progress is needed (such as development of efficient battery-electric heavy goods vehicles, or heat pumps that can efficiently provide heat in very cold climates) as well as substantial reinforcement of electricity networks. Furthermore, electricity will be used in sectors that have no history of using electricity, such as process heat (e.g. the cement industry, refining and chemicals) and heavy road transport.

The issues identified above make reliance on electrification alone to achieve decarbonisation both more risky and more costly. Our analysis shows that EU targets are more likely to be achieved if zero carbon hydrogen from natural gas is included in the solution.

Recently, an increasing number of stakeholders (including the European Commission with its 'A Clean Planet for All' vision) have recognised the risks associated with delivering the 'All-Electric' pathway. They have called for a more balanced solution that utilises competition between all forms of energy to contribute towards a decarbonised energy system.

The analysis in this paper builds on Pöyry's Decarbonisation study, mentioned above, which compared an 'All-Electric' pathway with a more balanced 'Zero Carbon Gas' pathway. More details on these pathways are given in Section 2.1.

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10 Throughout this report, results are based on Europe defined as EU 28 plus Norway and Switzerland unless otherwise stated.

11 European Commission. "A Clean Planet for all. A European strategic long-term vision for a prosperous, modern, competitive and climate neutral economy." 2018.

12 Pöyry Management Consulting. "Fully decarbonising Europe's Energy system by 2050." 2018.

1.4 Methods of hydrogen production

1.4.1 Three ways of producing hydrogen

Three ways of producing hydrogen have been considered in this study: steam methane reforming, electrolysis and pyrolysis[13], all of which are described in Table 1 below.

Table 1 – Hydrogen production processes

Process	Description	Key advantages	Key challenges
	**Steam methane reforming (SMR)**[14] **is a thermal process already used today. Reacts methane (CH_4) with steam to produce hydrogen and CO_2.** In order to be carbon-neutral, it needs to be combined with carbon capture and storage (CCS) of the CO_2 produced.	Currently the most developed option, especially at scale, and as such presents the most cost-effective form of hydrogen production even with the addition of CCS	Complex storage of CO_2 gas. Political opposition to CCS in many countries.
	**Electrolysis is an existing technology (small-scale use) that splits water (H_2O) into hydrogen and oxygen using electricity.** Hydrogen produced can be only be considered zero carbon if the electricity used is itself zero carbon.	No direct carbon emissions and no other by-products that need to be stored	Higher cost, questions about scalability.
	**Pyrolysis is the decomposition of methane into hydrogen and solid carbon (C).** A developing technology, it has the potential to play an important role in hydrogen production in the future. Residual carbon is in solid rather than in gaseous form.	No complex CO_2 storage in underground caverns, as is the case with CCS. Solid carbon can be used in existing industries, such as carbon black for tyres, in concrete for construction, or new uses such as graphene.	Early stages of technology development.

It should be noted that electrolysis, while not leading to any direct emissions, can only be regarded as truly carbon neutral if the electricity that is used as an input into the process has been produced from a zero carbon source. If electricity is produced from a fossil fuel source without CCS, such as coal or natural gas, hydrogen from electrolysis would be associated with indirect carbon emissions.

SMR with CCS will be difficult in some countries, due to political and technical reasons. We have assumed that the availability of CCS in Europe is limited to Norway, UK, Belgium, Denmark, Ireland, Netherlands and Poland. The main factor is the access to offshore storage meaning only countries with easy and existing access to the North Sea and its storage facilities[15] can therefore utilise CCS, with the exception of Germany, where CCS faces strong political opposition.

The cost assumptions for each of these hydrogen production processes are described in Section 2.5.2.

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13 Other ways of producing hydrogen such as coal gasification, oil partial oxidation, algae photosynthesis, wood pyrolysis, or based on ethanol and methanol have not been taken into account. Currently 76% of world hydrogen production is from natural gas, using steam methane reforming, partial oxidation or auto-thermal reforming, and 23% from coal gasification. Hydrogen production by any of these methods requires CCS to avoid CO_2 emissions.

14 Both steam methane reforming (SMR) and auto-thermal reforming (ATR) are potential processes of splitting methane into hydrogen and CO_2. For the purposes of this paper, we will use the term SMR, but no particular preference is indicated through this.

15 Depleted gas fields or aquifers are required for storage of CO_2. While some onshore storage fields could be used, we assume that this would not be accepted by the public and therefore only offshore fields would be used.

1.4.2 Characteristics of pyrolysis

A key difference between this paper (and the analysis on which it is based) and most other publications about decarbonisation of the energy sector is the inclusion of pyrolysis as a technology to produce hydrogen. For the purpose of this analysis, we have included the pyrolysis process as a method to produce hydrogen from 2030 in all of the countries that are studied.

Pyrolysis may provide hydrogen at reasonable cost and sufficient scale, and alleviate some of the concerns associated with CCS. Another potential benefit of pyrolysis is the production of solid carbon products, which can be utilised in other processes, thus creating additional value.

More detail on the development and potential of the pyrolysis process is given in the box below.

Methane Pyrolysis

Methane pyrolysis (also known as methane splitting or thermal decarbonisation of natural gas) is an existing technology, which uses high temperatures to break down natural gas molecules (CH_4) into hydrogen (2 H_2) and solid carbon (C) products, such as carbon black or synthetic graphite. These solid carbon products should not be confused with soot or 'black carbon' which is the undesired by product of incomplete combustion. Methane pyrolysis is already used commercially to produce carbon black with hydrogen as a by-product. Interest and research in the technology has increased in recent years because of its potential to provide zero carbon hydrogen to replace fossil fuels and thereby reduce CO_2 emissions.

Different processes can be used in pyrolysis including thermal, catalytic and plasma based technologies. The energy required for the pyrolysis reaction can be provided by electricity (for example from renewables) or from the natural gas feedstock or the hydrogen produced as part of the process. If biogas or biomethane are used as a feedstock then the process can result in negative emissions.

The methane pyrolysis technology has been assessed against the existing hydrogen production technologies, such as, steam reforming and electrolysis in six different environmental impact categories according to the Life Cycle Analysis (LCA) methodology [ISO 14040, ISO 14044]. The results of that study showed that the use of methane pyrolysis based on liquid metal technology for hydrogen production has a comparable Global Warming Impact to hydrogen production from renewables.

Markets already exist for solid carbon, which therefore creates value that can offset the cost of the hydrogen production. Carbon black is used in the production of car tyres, providing reinforcement, and also as a pigment in plastics, inks and paints. Other uses for carbon black include as an Ultra Violet (UV) stabiliser in plastic pipes, and in electronics. Carbon black can be formed into pellets to make handling easier. Carbon black is non-toxic and will not leach or release any constituents to the groundwater if stored underground.

Another solid carbon product, synthetic graphite, can be used in Lithium Ion batteries as the anode. Lithium Ion batteries are widely used in portable electronics such as smartphones, cordless appliances such as vacuum cleaners or power tools, and electric vehicles. Synthetic graphite can also be used in steel making as the electrode in electric arc furnaces, or as a refractory (heat resistant material) in furnaces and crucibles. Synthetic graphite can replace naturally occurring graphite, which is mined, 69% of it in China. The European Commission has identified the EU's dependence on imported raw materials for batteries as a source for concern.

Other carbon products include graphene, carbon fibre and nanotube carbon. Carbon fibre is used as part of composite materials in applications such aerospace and cars, wind turbines and construction. Graphene, which is a special form of graphite, is a relatively new material, known for its high strength and conductivity. Potential applications include semi-conductors, batteries and electronics. Nanotube carbon is used in polymers, plastics and batteries.

Methane pyrolysis offers the opportunity of producing decarbonised hydrogen and a potentially valuable by product throughout Europe (i.e. wherever is connected to the current natural gas grid). It can therefore support wider European industry as well as help meeting Europe's decarbonisation goals.

Sources:

IEA. "The future of hydrogen." 2019.

Dagle, Dagle, Bearden, Holladay, Krause, Ahmed. „An Overview of Natural Gas Conversion Technologies for Co-Production of Hydrogen and Value Added Solid Carbon Products." 2017.

EU Commission. "Staff Working Document Report on Raw Materials for Battery Applications." 2018.

Postels, Abanades, von der Assen, Rathnam, et. al. "Life cycle assessment of hydrogen production by thermal cracking of methane based on liquid-metal technology." 2016

Weger, Abanades, Butler. "Methane cracking as a bridge technology to the hydrogen economy. International Journal of Hydrogen Energy." 2017.

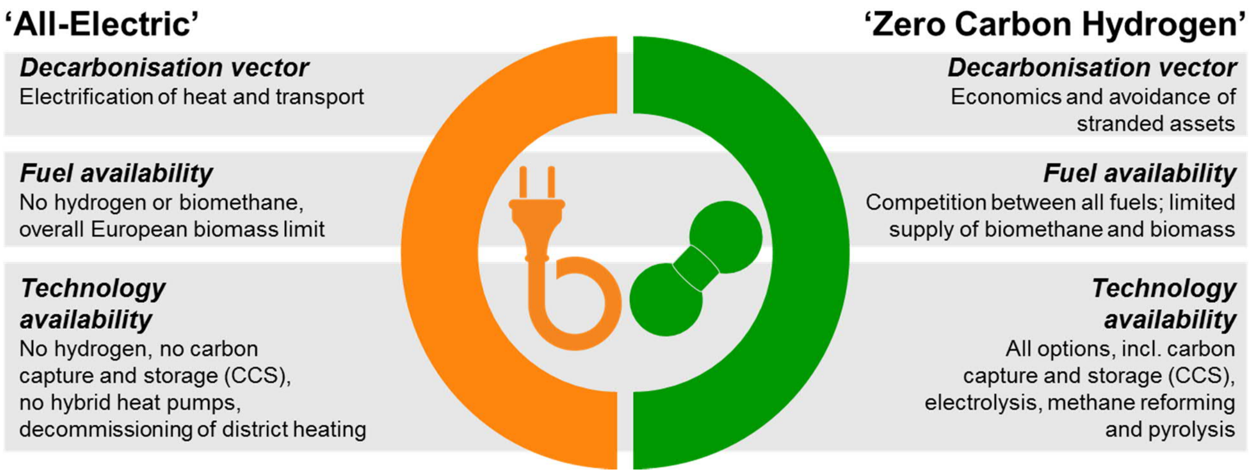
2. ZERO CARBON HYDROGEN FROM NATURAL GAS – THE KEY TO DECARBONISATION

2.1 ‘Zero Carbon Hydrogen’ pathway overview

In this paper, we use our analytical framework to compare two pathways, the ‘All-Electric’, and the ‘Zero Carbon Hydrogen’ pathway. The former is a pathway to decarbonisation that relies mostly on renewable electricity, but also requires significant amounts of nuclear power, biomass and interconnection. The ‘Zero Carbon Hydrogen’ pathway, on the other hand, allows all forms of clean energy compete with the most economical solutions being chosen through our decarbonisation modelling suite, described in (description see Annex A).

A high-level description of both pathways is given in Figure 2.

Figure 2 – High-level description of ‘Zero Carbon Hydrogen’ pathway



Whilst in the ‘All-Electric’ pathway, hydrogen is not included in the solution, the ‘Zero Carbon Hydrogen’ pathway results in a substantial use of hydrogen in all segments of the energy sector. Our analysis shows that hydrogen allows for a more efficient deployment of renewable electricity sources in the power sector[16] and a more efficient deployment of alternative technologies in the heat and transport sectors.

The following sections provide an overview of the transition towards a zero carbon energy economy in each sub-sector.

2.2 ‘Zero Carbon Hydrogen’ pathway: heat sector transition

Figure 3 demonstrates the variety of technologies that contribute to the decarbonisation of the heat sector towards 2050. The chart splits the heat sector into non-process and process heating. Non-process includes space and water heating in all buildings, whilst process heating is used for industrial processes in several industries (e.g. metal, glass, plastics, rubber and ceramics production).

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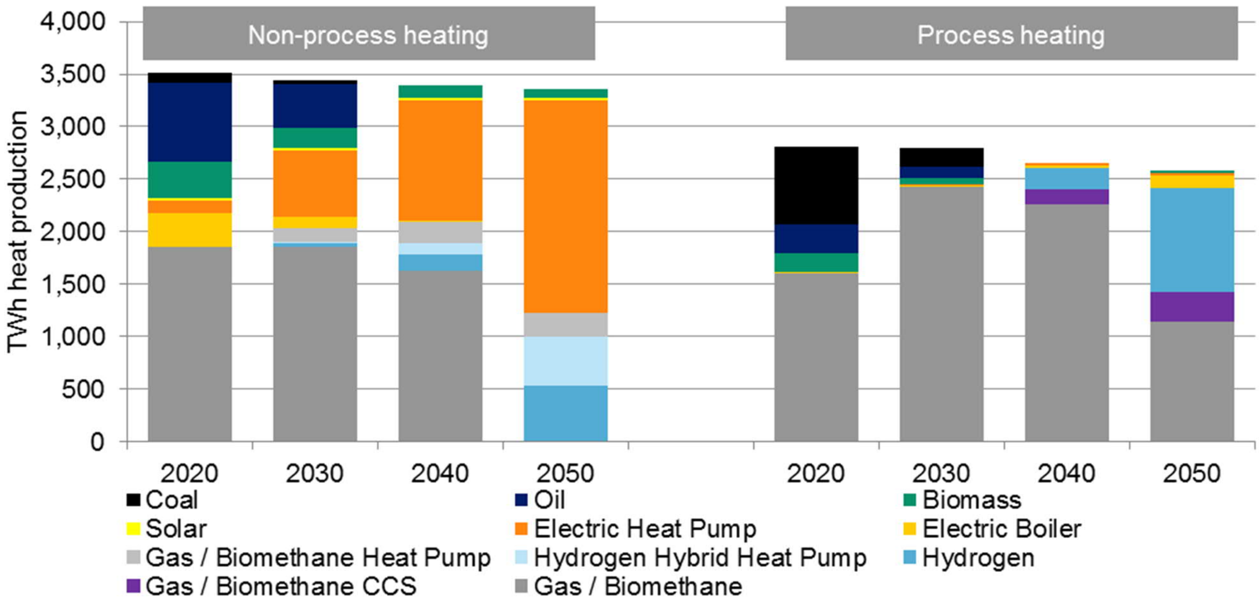
[16] Hydrogen fuelled plants can be operated when renewables are not available, and to account for seasonality of demand – reflecting much higher demand in winter, when electricity is also used for heating – which avoids having to overbuild renewables.

Figure 3 – Europe's heat sector under the 'Zero Carbon Hydrogen' pathway (TWh)



In the non-process heat segment, a combination of heat pumps and hydrogen boilers is deployed in the transition to a fully decarbonised sector. While heat pumps offer very high efficiency in providing heat, several considerations can make their use impractical, including:

- extremely cold weather (efficiencies of heat pumps can drop dramatically when temperatures reach very low levels, such as -10° or lower);
- poor insulation (heat pump efficiencies rely on very well insulated properties, which is not a given in many existing buildings across Europe); and
- convenience issues (replacing old systems will mean substantial changes to living spaces, including replacement of radiators, or installation of under-floor heating, since heat provided from heat pumps is less intense).

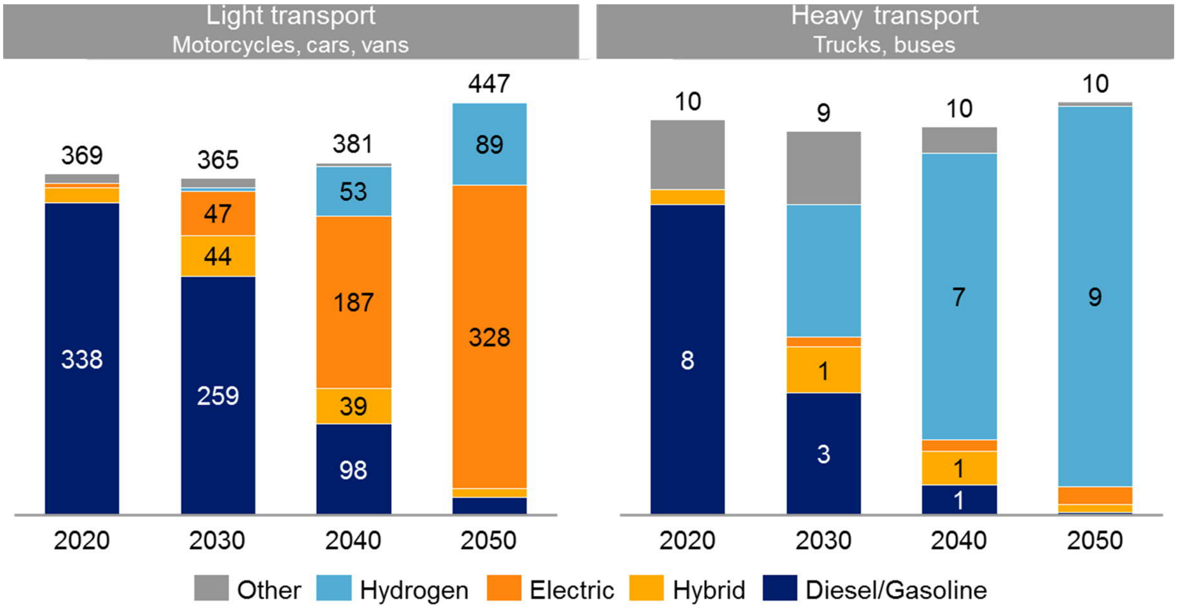
In those situations where heat pumps are impractical, hydrogen boilers provide a viable alternative, sometimes in hybrid systems together with heat pumps.

Hydrogen plays a key role in the process heat segment. Providing very high temperatures with electricity is challenging, which limits the effectiveness of electricity in this sector. Use of natural gas with post combustion CCS is a relatively low-cost option of decarbonising heat in this sector based on the assumptions used in this study. However, CCS may not be available in many countries for technical, economic or political reasons. Hydrogen is the most economical alternative in the other countries that don't allow the development of CCS. More detail on hydrogen use and supply is given in Section 2.5.1.

2.3 'Zero Carbon Hydrogen' pathway: transport sector transition

The transport sector undergoes a major transformation from oil-based fuels to using a combination of electricity and hydrogen, as shown in Figure 4.

Figure 4 –Europe's transport sector under the 'Zero Carbon Hydrogen' pathway (mn vehicles)



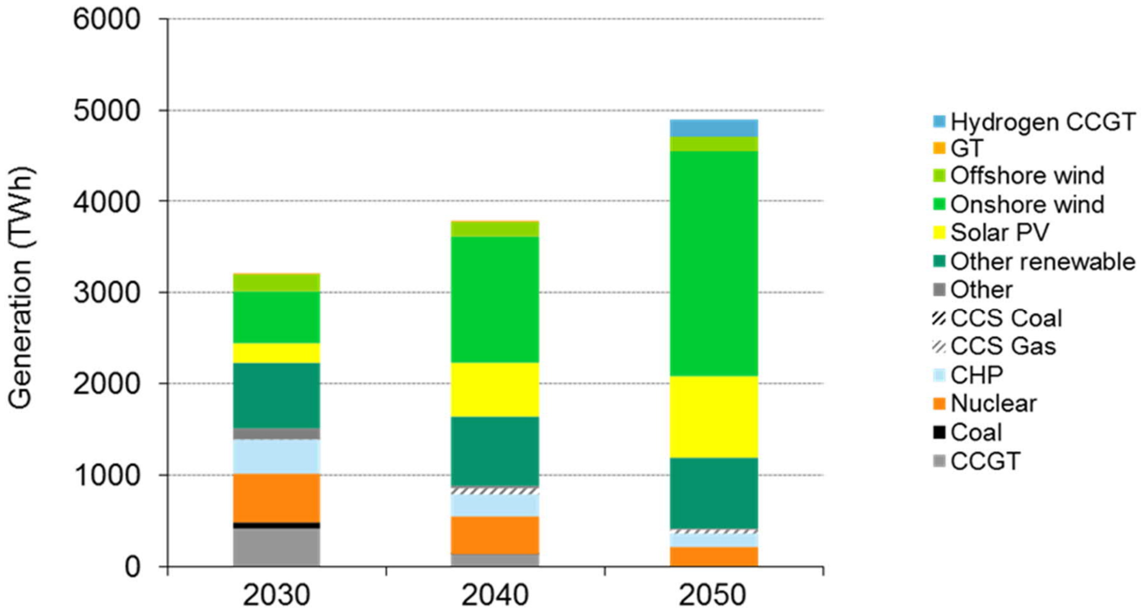
In the light transport segment, including motorcycles, cars and vans, battery electric vehicles account for the majority of vehicles on the road in 2050. However, in heavier transport segments, such as trucks and buses, the larger battery sizes that would be required and longer journeys make the use of electric vehicles impractical. In these segments, hydrogen fuel-cell vehicles provide an efficient alternative.

2.4 'Zero Carbon Hydrogen' pathway: power sector transition

Due to the large increase in the use of electricity in heat and transport, power demand grows from around 3,330TWh in 2020 to around 5,000TWh in 2050.

The majority of electricity will be produced by renewables, including 54% from wind, and 18% from solar PV, as shown in Figure 5. Currently, coal, gas and nuclear power plants provide electricity when renewables are not available. After these plants have been decommissioned, there is still a need for similar back up generation. This is provided in part by interconnection flows (within Europe) and flexible hydro generation (most notably in the Nordics), but the system also requires some additional power plants. Where available, natural gas power plants with post combustion CCS (41TWh in 2050) are used, but in countries where CCS is not available, hydrogen CCGTs (192TWh in 2050) fulfil this role.

Figure 5 – Europe's power generation transformation – 'Zero Carbon Hydrogen' pathway



2.5 Details of the hydrogen economy

2.5.1 Hydrogen demand and supply overview

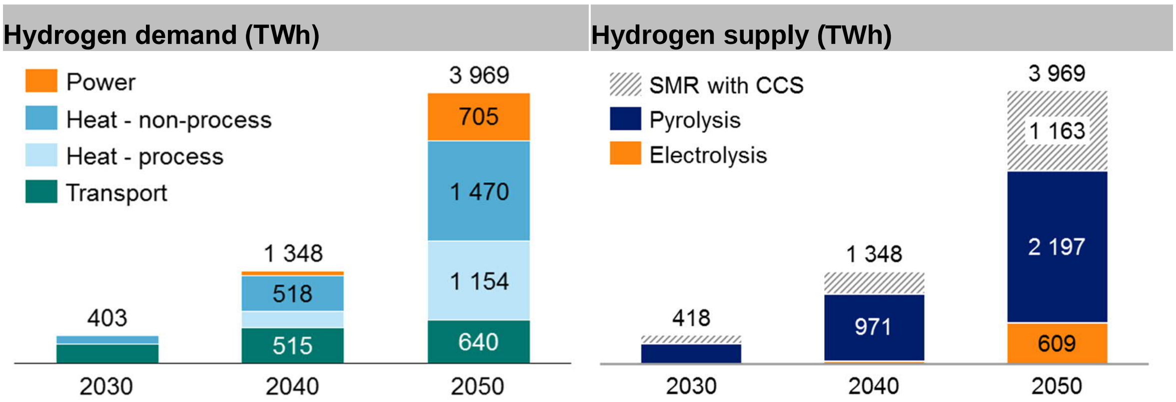
In the 'Zero Carbon Hydrogen' pathway, hydrogen is used to provide flexibility to the electricity system, but even more so to provide energy to sectors that would otherwise be difficult to decarbonise. Figure 6 shows the demand and supply of hydrogen in the pathway over time.

Hydrogen demand grows in all investigated sectors[17]. Transport and non-process heat use hydrogen from 2030, while hydrogen used in CCGTs to generate power only develops in the 2040s. Total hydrogen demand is close to 4,000TWh by 2050.

As SMR with CCS is the cheapest technology for producing hydrogen, most hydrogen will be produced from this source in the countries where CCS is available. In most other countries, pyrolysis is the primary source of hydrogen production. Electrolysis only occurs in significant volumes in regions with very low cost renewables, such as Iberia, or the Nordics as, otherwise, it would be more expensive than either SMR with CCS or methane pyrolysis.

17 There are several other potential uses of hydrogen that have not been taken into account as part of this study. These include fuel cells for residential heating, industrial processes, and waterborne transport or aviation.

Figure 6 – Hydrogen demand and supply



While hydrogen demand is seasonal (especially in the heat sector), most hydrogen production facilities have a high share of capital and fixed costs, and are designed to run at very high load factors. Therefore, hydrogen storage is important to balance energy between seasons[18]. Around 370TWh of hydrogen storage is needed across Europe, while some hydrogen can also be used in CCGT power plants (for example when stores are full or renewable generation is low).

Natural gas remains an integral part of the energy mix due to its role in producing clean hydrogen in this pathway. Natural gas continues to be transported across the existing transportation pipelines, however, overall consumption of natural gas in the energy sector in 2050 is very close to today's levels (~2% decrease). By 2050, just 12% of total natural gas volumes[19] will be used as an end-use fuel (in CCS installations), whilst the majority (88%) will be the feedstock for hydrogen production, most of which feeds into converted distribution networks, and some is used in power generation.

2.5.2 Cost of hydrogen production

This section provides an overview of the technology costs for hydrogen. Hydrogen production costs are expected to fall over time, as the technologies develop. The key parameters for the hydrogen production technologies are given in Table 2[20]. Notably missing from this table are costs for feedstocks, since those change over the course of years, days (and, in the case of electricity, hourly).

[18] There is a trade-off between using existing natural gas storage and producing hydrogen when it is needed, and producing hydrogen continuously and then storing it in hydrogen storage facilities. Because of the high capital costs of pyrolysis and SMR with CCS, continuous production is more economical. It has therefore been assumed in this study that hydrogen is produced in this manner and then stored, if necessary.

[19] While CO_2 is the most well-known, other gases play roles in climate change. In the context of natural gas production and transportation, methane leakage is an issue, as methane is a potent greenhouse gas. In this study, the topic has not been assessed specifically, but it should be noted that (1) effects from methane leakage would be expected to decrease in a world where distribution networks are converted to hydrogen, and (2) pyrolysis can play a role in creating negative emissions (in combination with the usage of biogas, biomethane and CCS) to offset these effects.

[20] Sources: SMR with CCS and Electrolysis: E4tech, UCL Energy Institute, and Kiwa Gastec."Scenarios for deployment of hydrogen in contributing to meeting carbon budgets and the 2050 target. Final Report." 2015.; Pyrolysis: Pöyry analysis based on Brett Parkinson, P. Balcome et al. "Hydrogen production using methane: Techno-economics of decarbonizing fuels and chemicals." 2017.

Table 2 – Hydrogen production cost parameters in 2050

	Capex (€/kW H_2)	Opex (€/kW H_2/yr)	Efficiency	Levelised cost[21]
SMR with CCS[22]	934	37	78	47
Pyrolysis	1261	22	55	60
Electrolysis	544	31	80	66

The key drivers for the wholesale costs of hydrogen are:

- **technology costs:** capex occupies a large share within the total cost of all hydrogen production technologies, especially for electrolysis;
- **input price:** the cost of gas and electricity are important drivers for the cost of hydrogen – higher gas prices and/or lower electricity prices (i.e. cheaper than expected renewables) could make electrolysis more economical relative to SMR with CCS or pyrolysis ;
- **cost of CO_2 storage:** SMR with CCS depends on the cost of transportation and storage of CO_2; and
- **value of solid carbon products:** markets for solid carbon products already exist but are relatively limited. If additional demand for solid carbon products materialises, pyrolysis can benefit from an additional revenue stream, thereby making it more commercially attractive. For the purpose of this study, no value has been attributed to the by-product of pyrolysis.

More information on the economics of pyrolysis as a hydrogen production technology can be found in papers by Parkinson et al[23],[24], and by Dr. Michael Faltenbacher[25].

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21 Assumes baseload operation of SMR and pyrolysis and a gas price of €20/MWh. For electrolysis, this assumes a 30% load factor and average electricity price of €30/MWh (assuming that the electricity price for the lowest priced periods for 30% of the time is €30/MWh on average). In order to achieve a higher load factor, electrolysers would have to buy electricity during periods when it was more expensive, thereby increasing the input price of electricity, and leading to higher levelised costs for the hydrogen produced. For example a 100% load factor for electrolysis would imply buying electricity at baseload (annual average) prices. As noted elsewhere in the report it does not make economic sense to overbuild renewable generation to enable cheap electricity for electrolysis.

22 Cost for CO_2 transportation and storage are included in these numbers.

23 Brett Parkinson, P. Balcome et al. "Levelized cost of CO2 mitigation from hydrogen production routes." 2018.

24 Brett Parkinson, P. Balcome et al. "Hydrogen production using methane: Techno-economics of decarbonizing fuels and chemicals." 2017.

25 Michael Faltenbacher. "GHG in the EU Energy Market today and in 2050. Reduction potential of Natural gas and hydrogen." 2018.

3. BENEFITS OF ZERO CARBON HYDROGEN FROM NATURAL GAS

3.1 Summary – the key to deep decarbonisation

Renewables will play a significant role in all pathways as a cost-effective form of clean energy in the future. In the 'Zero Carbon Hydrogen' pathway, renewables dominate in the power sector, and passenger vehicles and non-process heat sectors are electrified. Hydrogen makes a significant contribution to the heavy transport and process heat sectors and allows non-process heat to decarbonise where electrification is not feasible.

Relying on very high levels of electrification in an 'All-Electric' future is a high risk strategy. EU targets are more likely to be achieved if hydrogen from natural gas is included in the solution. The 'All-Electric' pathway relies on new nuclear, fast grid reinforcement and a solution to the inherent lack of seasonal storage. It also risks failing to decarbonise sectors that cannot easily be electrified raising the real possibility that overall decarbonisation targets may be missed. Table 3 provides an overview of key risks associated with different decarbonisation pathways.

Table 3 – Risks to decarbonisation and impact in different pathways

Risk description	Risk in 'All-Electric'	Risk in 'Zero Carbon Gas'	Risk in 'Zero Carbon H_2'	Comments on benefits of 'Zero Carbon Hydrogen' pathway
Heavy goods electric vehicles are technically infeasible within timeframe	✖	*none*	*none*	Hydrogen provides alternative in heavy transport
Biomass supply chain cannot deliver the volumes needed for power and heat	✖	*none*	*none*	Very limited use of biomass in transport, heat and power
Nuclear power faces greater than expected political opposition	?	*none*	*none*	Limited reliance on nuclear power, no new power plants built
Nuclear power cannot be operated flexibly (e.g. turn off for several days)	?	$	$	
Heat pumps fail in cold conditions long before the suggested -15º	?	$	$	Reduced reliance on heat pumps due to use of more stand-alone hydrogen boilers
Heat pump supply chains do not develop quickly enough	$	$	$	
Energy efficiency in houses evolves slower than expected, making heat pumps impractical	$	$	$	
Electricity grid reinforcement (incl. distribution, transmission, interconnection) cannot keep pace with demand and renewables growth	?	$	$	Gas grids and hydrogen use provide alternative energy source
CCS faces greater than expected political opposition or technical obstacles	*none*	?	$	Methane pyrolysis offers viable alternative of providing energy (hydrogen)

✖ Risk of missing targets – no other option available; ? Significant cost increase, risk of missing targets; $ Cost increase

Zero carbon hydrogen produced from natural gas can significantly reduce these risks when used as part of the energy mix. It can therefore be an essential complement to renewables for the successful deep decarbonisation of the European economy.

Development of pyrolysis will allow cost-effective, practical and secure development of hydrogen at scale and foster competition in the energy sector. Pyrolysis has key advantages – it is cheaper and more scalable than electrolysis and overcomes many of the barriers associated with widespread deployment of CCS (which would be necessary for SMR to produce zero carbon hydrogen).

In the following sub-sections, we present supporting evidence for these messages. Section 3.2 explains how hydrogen from natural gas can reduce the risk of not meeting decarbonisation targets. Section 3.3 demonstrates how hydrogen from natural gas allows cost-effective, practical and secure development of hydrogen at scale. Finally, in Section 3.4 we explain why the pyrolysis production method is key to achieving the deep decarbonisation required to meet Europe's targets.

3.2 Zero carbon hydrogen reduces the risks of missing decarbonisation targets

Pöyry's 'Full Energy-Sector Decarbonisation Study' highlighted the risks associated with an 'All-Electric' solution. Table 3 sets out the main risks of pursuing an 'All-Electric' route and shows how hydrogen can help to mitigate these risks by providing credible and reliable alternatives.

Allowing hydrogen to play a role in the energy mix:

- reduces the need for new nuclear power;
- mitigates the performance risks of heat pumps in very cold temperatures;
- reduces the need for electricity network reinforcements; and
- reduces the need for investment in electricity interconnection;

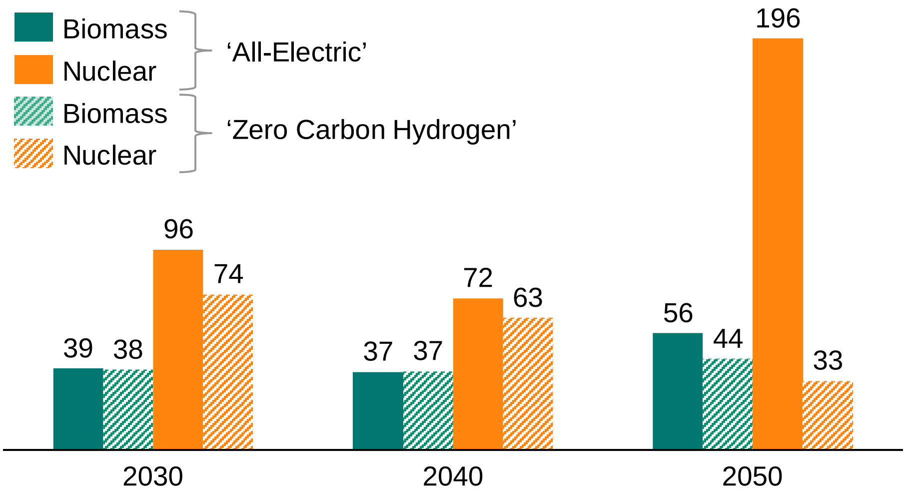
and therefore significantly reduce the delivery risk (and cost) compared to an 'All-Electric' pathway.

Zero carbon hydrogen reduces the need for new nuclear power

In an 'All-Electric' pathway, most, but not all, energy needs can be covered by renewables. A significant growth in nuclear and/or biomass is needed to provide baseload generation, which cannot be achieved with renewables alone. Figure 7 shows the difference in requirements for both nuclear and biomass in the 'All-Electric' and 'Zero Carbon Hydrogen' pathways. In particular, nuclear generating capacity requires a significant increase between 2040 and 2050 (a net increase of 124GW from 72GW to 196GW). Conversely, nuclear capacity reduces in the 'Zero Carbon Hydrogen' pathway (from 63GW to 33GW) as overall electricity demand is lower due to the existence of alternative energy carriers – in this case hydrogen.

If, in the 'All-Electric' pathway, this expansion of nuclear generating capacity cannot be achieved in time – for political, technical or economic reasons – then it may be too late to deploy zero carbon alternatives in order to meet demand. By this time, other technologies will have been excluded from the energy mix and gas networks may be redundant. Thus, a lock-in to electrification is created by not allowing zero carbon gases in the solution. For example, gas boilers would disappear in favour of heat pumps, before hydrogen can develop at scale. Thus, incentives for further developing hydrogen technologies are weak and innovation would stall.

Figure 7 – Comparison of nuclear and biomass requirements in the pathways (GW)



Zero carbon hydrogen mitigates the performance risks of heat pumps in very cold temperatures

Another key risk relates to performance and practicality of heat pumps. There are uncertainties with regards to heat pump effectiveness in cold climates, especially in poorly insulated, older buildings. This raises the risk that homes and properties may not be sufficiently warm at times of need.

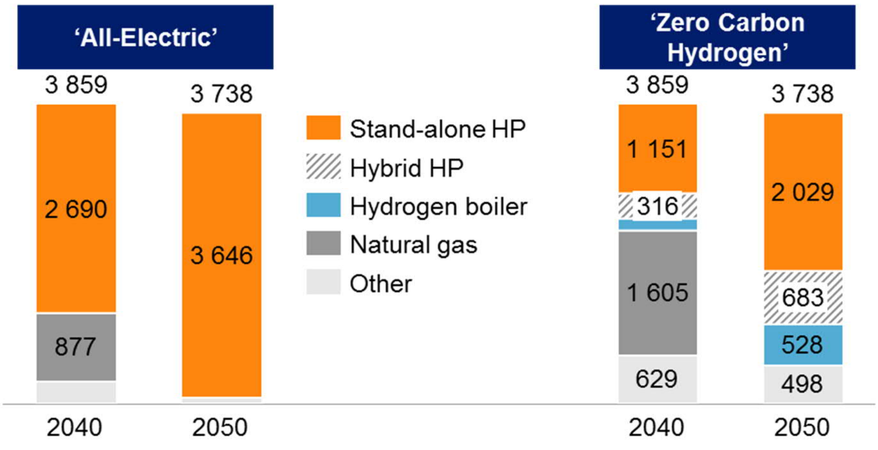
The process of switching a property from gas heating to a heat pump is complex and requires sufficient space and access, as well as new radiators and pipework. The installation costs and inconvenience are high, and raise the question about how this will be financed and how households could be compelled to switch. The conversion will require the scale up of a trained and flexible workforce, so there is a risk that the supply chain may not be able to deliver the number of conversions that are required in the 'All-Electric' pathway.

By contrast, the switch from a gas boiler to a hydrogen boiler is a much simpler process and can be achieved by the replacement of the burner nozzle at the right time. 'Hydrogen-ready' gas boilers are being developed already. These can be installed when existing boilers are due to be replaced and converted quickly once hydrogen becomes available[26]. Existing internal pipework and radiators are not affected. Historic parallels for this type of conversion exist, namely the conversion from 'town gas' (which was itself a mix of hydrogen, and carbon monoxide produced via coal gasification) to natural gas in the UK in the 1960s and 1970s.

Zero carbon hydrogen potentially gives householders a choice of technologies when deciding how to decarbonise their home heating. This increases the likelihood that the decarbonisation of heating will be achieved on time by improving public acceptance and conversion rates.

Figure 8 shows heat production in both pathways. By 2050, the 'All-Electric' pathway relies almost exclusively on heat pumps in space and water heating, regardless of whether the deployment is feasible or practical. There are no other alternatives available. The 'Zero Carbon Hydrogen' pathway, however, allows a more balanced approach to supplying heat. Alternative technologies are deployed where they are most suited. By utilising hydrogen boilers and hybrid heat pumps alongside stand-alone heat pumps, heat demand can be met with a reduced risk of failure.

Figure 8 – Reliance on heat pumps in 'All-Electric' vs. 'Zero Carbon Hydrogen' pathways (TWh of heat production)



Note: 'Other' includes district heating, CHP, biomass boilers, solar thermal, and several other less common technologies.

Zero carbon hydrogen reduces the requirement for network reinforcement

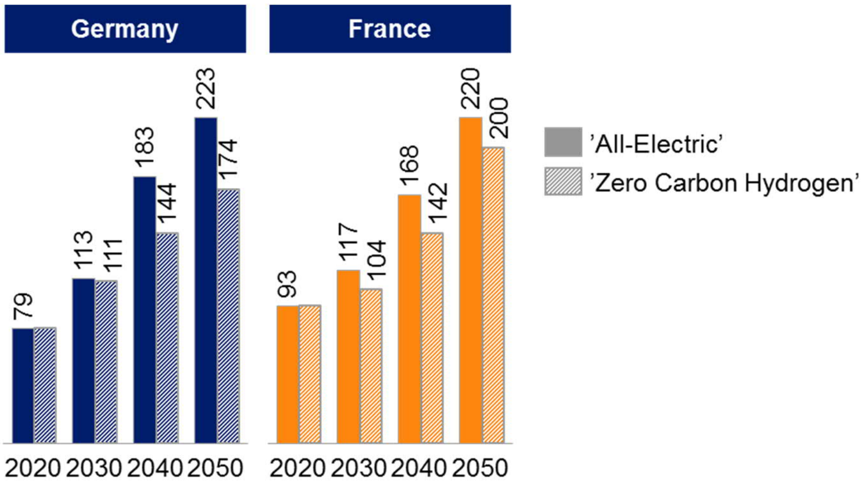
An 'All-Electric' solution requires a fast and considerable amount of reinforcement and extension of the power grid, most significantly between 2030 and 2040. This is necessary for all levels of the electricity grids, but especially at the distribution and local level due to the upgrades required to local substations,

26 Frazer-Nash Consultancy for the UK Department of Business, Energy and Industrial Strategy. "Logistics of Domestic Hydrogen Conversion." 2018.

transformers and underground cables to meet demand from heat pumps and electric vehicles. This is greater in the ‘All-Electric’ pathway as the demand from electric vehicles and heat pumps is much higher.

Figure 9 shows the pace and scale of peak demand growth in the ‘All-Electric’ and the ‘Zero Carbon Hydrogen’ pathways as a proxy of network reinforcement needs. Here, utilising hydrogen instead of an ‘All-Electric’ solution leads to a later, and less significant need for network expansion[27]. Reducing the need for electricity network expansion reduces costs since on an energy basis, gaseous energy carriers (such as biomethane or hydrogen) are cheaper to transport compared to electricity.

Figure 9 – Peak demand growth (GW) in Germany and France



Hydrogen reduces the reliance on and investment in electricity interconnection

Increasing renewables deployment also requires an increase in electricity interconnection between countries. This is because the potential for renewable technologies differs significantly between regions – for example, Southern Europe has excellent solar PV potential, whilst the North Sea region has strong potential for wind resources. Interconnection allows excess renewable generation in one country to be supplied to meet demand in an adjacent country and thus improves the efficiency of investments in renewable generation and transmission capacity.

However, new or reinforced interconnections require strong collaboration between countries and complex mechanisms to allocate costs between them. Experience with current ‘European Projects of Common Interest’ shows that delays are common[28]. There is a risk that increased interconnection is not wholly achieved resulting in decarbonisation being delayed or not delivered. Figure 10 shows the reduced need for interconnection in the ‘Zero Carbon Hydrogen’ pathway, as a result of a reduced reliance on renewable electricity.

The reduced requirement for interconnection in the ‘Zero Carbon Hydrogen’ pathway not only makes decarbonisation more achievable, but also means that it can be delivered at a significantly lower cost.

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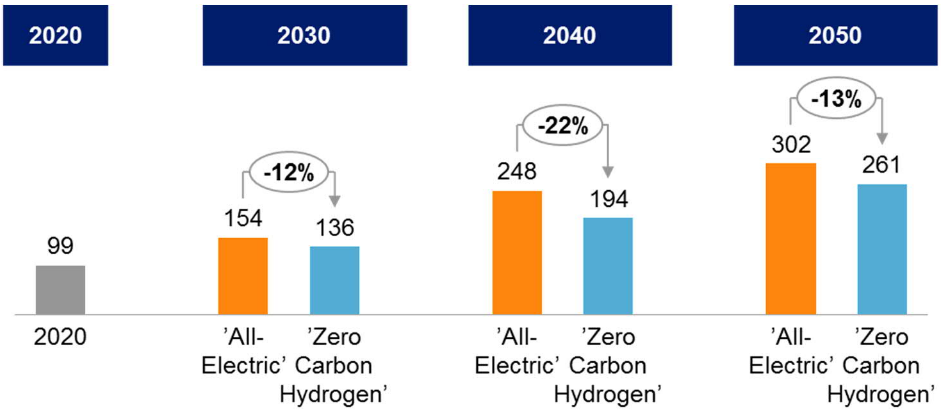
27 Examples for problematic electricity network expansion can be found in Germany, where grid operators face higher costs and challenges in transporting wind power from the North to demand centres in the South, or in Britain, where Scotland and Southern England are linked with high-voltage direct current sub-sea cables, in order to avoid onshore reinforcement.

28 See Section 1.2.3 of “Consolidated Report on the progress of electricity and gas Projects of Common Interest for the year 2017”. Agency for the Cooperation of Energy Regulators. July 2018.

Figure 10 – Interconnector capacity (GW) in 'All-Electric' vs. 'Zero Carbon Hydrogen'



3.3 Zero carbon hydrogen from natural gas allows cost-effective, practical and secure development of hydrogen at scale and fosters competition in the energy sector

In the previous section, we demonstrated how the use of hydrogen in the energy mix reduces the risks of failing to meet decarbonisation targets. In this section we show how hydrogen produced from natural gas allows **cost-effective**, **practical**, and **secure** development of hydrogen at scale. As described in Section 1.4 we consider hydrogen production from electricity (via electrolysis) and natural gas (via either steam methane reformation with CCS, or pyrolysis).

Cost advantages of zero carbon hydrogen from natural gas

As we have demonstrated in Section 2.5.2 and Table 2, producing hydrogen from natural gas is more **cost-effective** than electrolysis in most countries in Europe. This is the case for both SMR with CCS and pyrolysis.

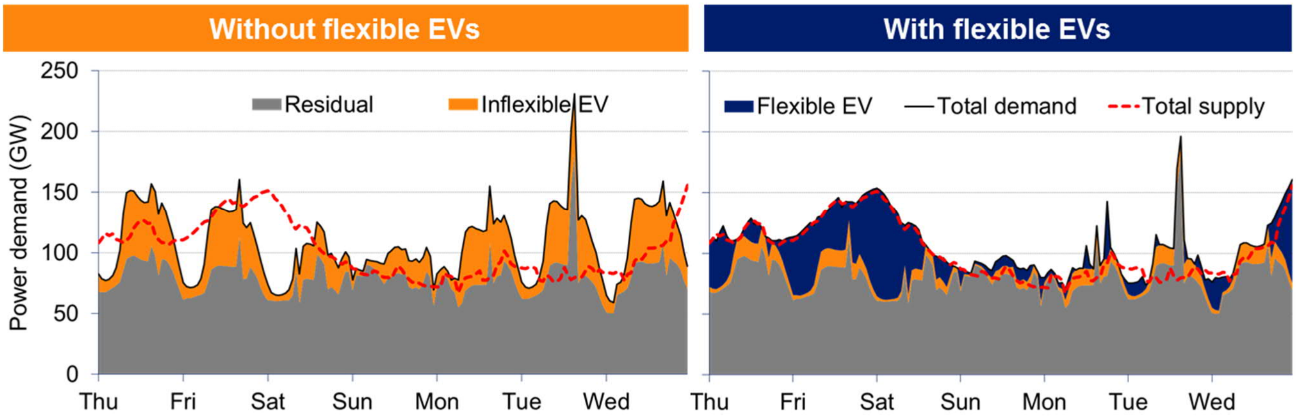
The main drivers of hydrogen production costs are the fixed costs and the 'input price' – either electricity or natural gas. The competitiveness of electrolysis versus either SMR with CCS or pyrolysis is therefore dependent on the relative prices for electricity and natural gas.

Renewables are inherently intermittent and only generate electricity when wind speeds or solar irradiation are sufficient. Neither is it 'dispatchable' unlike coal and gas generation, meaning that the electricity system operator cannot call upon renewable generation to produce electricity when it is required by the system. The lack of control over renewable generation means that, at times, there may be too little available to meet demand and therefore 'back-up' dispatchable generation is required. At other times, there may be an excess of renewable generation over demand leading to the 'curtailment' or switching-off of wind and solar, associated with electricity prices dropping to zero or even negative.

The competitive production of hydrogen by electrolysis depends on a significant number of these periods of low, zero or negatively priced electricity, as it can be more economical to produce hydrogen when electricity prices are low as an alternative to curtailment. The increase in the frequency of very low prices in several European markets in recent years (most notably in Germany) has led to a surge in the interest in electrolysers to produce hydrogen.

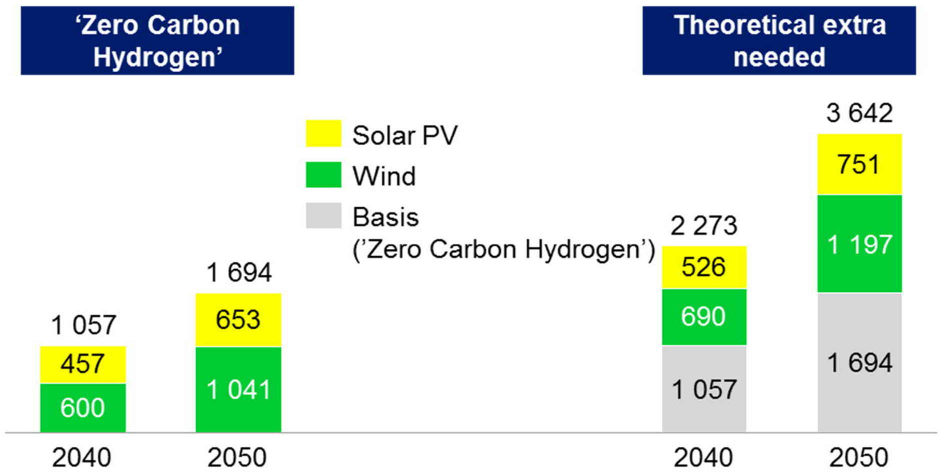
However, when assuming functioning market mechanisms, some flexible demand side response from electric vehicles and a level playing field for all technologies, our analysis shows that it is uneconomic to build a large amount of renewable electricity capacity if this leads to long periods of low or negative prices. Figure 11 shows how flexible demand can reduce curtailment (or low or negative prices) by shifting charging of EV batteries from low renewables periods (e.g. Monday, Tuesday in this example) to high renewables periods (Thursday and Friday).

Figure 11 – Impact if flexible EV charging on curtailment in Germany in a week in 2050



In the absence of significant periods of low or negative prices, renewable electricity capacity would need to be built and dedicated specifically for the production of hydrogen in electrolysis. 3,360TWh of hydrogen is produced from natural gas in 2050 in the 'Zero Carbon Hydrogen' pathway. If the same amount of hydrogen was produced from electrolysis, then renewable generation capacity would need to double above that already needed to meet transport, heat and regular power demand (115% higher). Assuming an equal percentage increase across technologies, solar capacity would need to increase by another 751GW in 2050, and wind by another 1,197GW, over that already required in the 'Zero Carbon Hydrogen' pathway, as shown in Figure 12. The additional capex for this capacity would be close to €2 trillion, not including the cost for converting the gas transmission network to hydrogen and potential further expanding the network.

Figure 12 – Additional RES capacity needed to replace natural gas in hydrogen production (GW)



Practical benefits of zero carbon hydrogen from natural gas

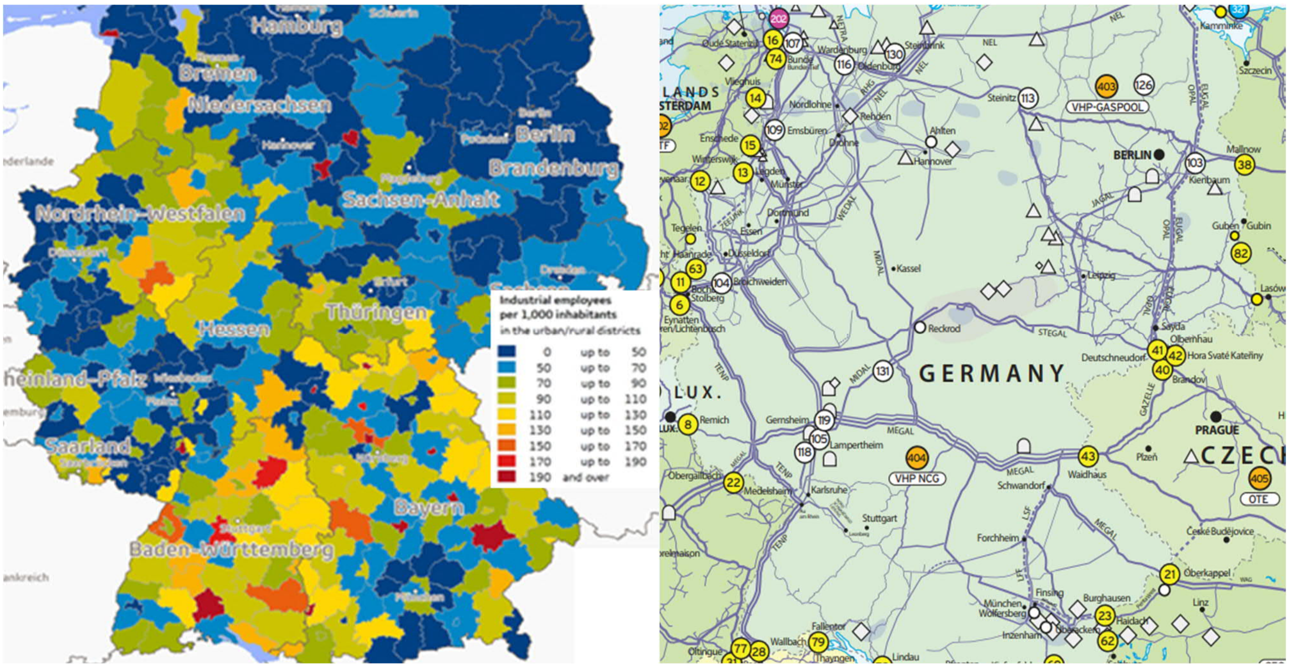
The practical benefits of zero carbon hydrogen from natural gas become clear when we consider the logistics of hydrogen production and supply. Aside from the issues associated with the scale and costs of electrolysis, we also consider the locations of hydrogen production. If hydrogen is produced from electrolysis, it will need to be produced in areas and regions with a strong potential for renewable electricity in order to be economic. (Using nuclear power for electrolysis would be much more expensive). Examples are Iberia and Southern Italy for solar PV, and the North Sea region for wind.

In such a case, hydrogen would then have to be transported via transmission pipelines over hundreds of kilometres to demand centres that could be in different countries. A hydrogen transmission network would need to be developed – either by repurposing the existing gas transmission network or by constructing new hydrogen transmission pipelines. In that case, there would be also be a requirement for many new transmission connection points linking both renewables generation to the electrolysers, and the electrolysers to the hydrogen transmission grid. This would increase costs and complexity significantly.

The alternative, and more feasible, approach is to produce hydrogen from natural gas closer to demand centres, thus removing the requirement for a hydrogen transmission network to be developed. Pyrolysis enables zero carbon hydrogen to be produced in areas that cannot easily access the CCS required for SMR production of zero carbon hydrogen, or which are far from renewables production. Consequently, zero carbon hydrogen production is theoretically available to any area with a natural gas transmission connection.

Existing gas transmission pipelines could continue to carry natural gas throughout Europe, as they do today. Natural gas would be offtaken from the transmission grid and then converted into hydrogen before being injected into the distribution grid. This would limit any disruption and conversion necessary to the distribution networks. Across Europe, there is a good match between natural gas transmission infrastructure and industrial clusters or major population centres, since pipelines were built to transport gas to these locations.

Figure 13 – Comparison between industrial clusters and gas infrastructure in Germany



Sources: GfK (industrial density), Entsog (gas transmission infrastructure)

Continuing to use the transmission networks to transport natural gas, whilst producing hydrogen at the local level, also enables a more feasible transition to a decarbonised economy. Whilst the gas transmission networks continue to carry natural gas, individual distribution networks can be converted to carry hydrogen in a phased and planned roll out. If the transmission grid were converted to hydrogen, all the connecting distribution grids and their customers would have to be ready to switch to hydrogen at the same time. Such an approach would place a severe strain on the supply chain (for example, the need for gas engineers to visit every home to make sure all appliances are capable of switching).

There is also the potential to blend hydrogen into the either the transmission grid or the distribution girds as an intermediate step before completely switching to hydrogen. Carbon emission savings would depend on the quantity of zero carbon hydrogen blended, and limits for this in countries vary.

Security of supply and competitive benefits of zero carbon hydrogen from natural gas

Natural gas, and the hydrogen produced from it, will continue to utilise existing European gas assets including LNG import terminals, storages and pipeline interconnections. The existing European gas infrastructure has been developed over many years and has a proven track record of providing secure gas supplies to end consumers. Although indigenous supplies may decline over the period, there are diverse and secure supply routes into Europe.

There will also be advantages to electricity security of supply as existing generating assets can be converted to operate on hydrogen rather than natural gas. This will enable dispatchable generation (CCGTs and OCGTs) to continue to provide flexibility and back-up to renewable generation. These plants would be used in the same way as today, and will also help avoid investment in more expensive options, such as grid battery storage.

It is clear that there is not one single solution that can solve all challenges with decarbonisation. Therefore, in order to ensure consumers have a choice but also to ensure the competitiveness of European industry, competition in all parts of the energy sector is vital. Utilising natural gas as the main source of hydrogen production contributes to competition in the energy markets.

In a future where zero carbon hydrogen is produced from natural gas, the gas wholesale market could continue to operate in a similar way to today. Instead of gas being used predominantly as an end use fuel, it would become mainly a feedstock for zero carbon hydrogen. As different companies (for example utilities, industrial users) could produce hydrogen there would continue to be many different buyers on the wholesale market, as there are today. The supply of natural gas would be largely unchanged. European buyers of natural gas would continue to benefit from the competition between indigenous production, pipeline imports and LNG as they do today. As gas demand would remain significant (see Section 2.5.1 above) the market would be of sufficient size to enable liquid trading as well as being attractive to natural gas producers from abroad.

There would also be no need to wait for a deep and liquid traded hydrogen market to develop whilst grids are switching from hydrogen to natural gas, as consumers would still benefit from gas to gas competition. Nonetheless, competition between different hydrogen producers could still develop. For example, hydrogen from electrolysis could compete with that from natural gas in areas with access to renewables and either pyrolysis or SMR with CCS.

3.4 Zero carbon hydrogen produced from pyrolysis reduces the risks of relying on CCS

So far, we have demonstrated that a future with hydrogen reduces the risks of Europe missing its decarbonisation targets. We have also shown why hydrogen from natural gas has significant advantages over hydrogen produced by electrolysis.

In our ‘Full Energy-Sector Decarbonisation Study’, the ‘Zero Carbon Gas’ pathway depended on the availability and widespread deployment of CCS to decarbonise industry, power and produce hydrogen at scale. We did not constrain the deployment of CCS in Europe for either political or technical factors. However, there is a risk that CCS may not be available in a number of EU countries. This may be due to political reasons – Germany remains a strong opponent of CCS – or technical issues, such as long transport routes from capture to storage and unavailability of storage sites within the country, as described in Section 1.4.1.

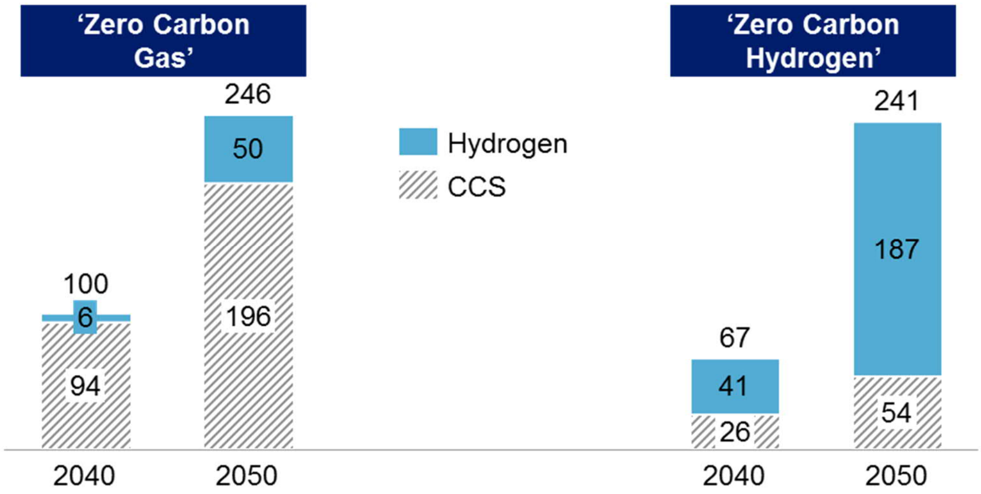
Pyrolysis reduces the risks of CCS not being widely available

In this study we have, therefore, limited the availability of CCS to a number of countries that have expressed support and have access to storage sites in the North Sea. In other countries, CCS is not available and other options to decarbonise and produce hydrogen at scale are required. This is because some sectors are impossible or unlikely to be decarbonised through electrification for reasons explored in this paper, as set out in Section 1.3.

In those countries where CCS is not available pyrolysis provides an alternative to both hydrogen production from SMR with CCS, and process heat decarbonisation using natural gas with post combustion CCS. The use of hydrogen provides a less disruptive, and politically and technically less challenging, way of decarbonising process heating. With post combustion CCS, industrial sites need to install carbon capture equipment, and secure access to CO_2 pipelines and storage. With conversion to hydrogen, the equipment is similar to a natural gas installation, and operation does not require the capture or transport of CO_2.

Figure 14 compares the installed capacity of both post combustion CCS and hydrogen in the process heat sector between the ‘Zero Carbon Gas’ and ‘Zero Carbon Hydrogen’ pathways. It can be seen that the strong reliance on CCS in the ‘Zero Carbon Gas’ pathway is significantly reduced in the ‘Zero Carbon Hydrogen’ pathway where there is a strong reliance on hydrogen from pyrolysis.

Figure 14 – CCS and hydrogen in 'Zero Carbon Gas' vs. 'Zero Carbon Hydrogen' pathways (GW of installed capacity in process heating segment)



Pyrolysis becomes a key enabler of decarbonisation with hydrogen

Pyrolysis becomes the key enabler of the development of a hydrogen based solution to decarbonisation:

- Hydrogen produced from pyrolysis provides an alternative to post-combustion CCS in order to decarbonise process heat in those countries where CCS is not available.
- Although production of hydrogen from pyrolysis is more expensive than SMR with CCS, it is cheaper than electrolysis on a LCOE (Levelised Cost of Energy) basis.
- Pyrolysis should also be more scalable than electrolysis –resources of affordable natural gas are readily available – enabling large quantities of hydrogen to be produced without the reliance on significant amounts of dedicated renewables.

It is less likely that a hydrogen based solution to decarbonisation could be achieved without pyrolysis and with the potential limitations of SMR with CCS. Producing hydrogen from electrolysis would significantly increase overall costs and make hydrogen less attractive. This would increase the risks of decarbonisation targets being missed.

4. CONCULSIONS AND POLICY RECOMMENDATIONS

Conclusions

In this paper we have shown that the most practical and economic pathway to decarbonisation includes hydrogen that is produced mainly from natural gas.

An 'All-Electric' future relies too heavily on new nuclear capacity, technological advances and enormous investment in power grid networks. In our view this reliance raises a very real risk to successful delivery that could conceivably result in missing decarbonisation targets.

This risk includes heavy reliance on interconnection between countries, which is challenging from both a technical and a political perspective. In a world of high renewable penetration, countries will have to co-operate stronger, but limiting the reliance on interconnection limits the risk.

A future that includes hydrogen, although still incredibly challenging to deliver, reduces these risks, could be cheaper to achieve and minimises the disruption that could be caused to end users. Whilst hydrogen produced from electrolysis has a role to play, the essential element to allow delivery of large-scale hydrogen deployment in heat, industry, transportation and power is the inclusion of hydrogen produced from natural gas. Pyrolysis becomes a key enabler to producing hydrogen at scale in those countries that do not support CCS for political or technical reasons.

Utilising natural gas to produce hydrogen comes cheaper compared to relying on electrolysis. While pyrolysis can rely on the availability of natural gas, electrolysis would require large extra capacities of wind and solar PV, over and above what is already necessary to meet power demand for lighting, appliances, industry, heat and transport.

Existing transmission networks can continue to transport natural gas to demand centres allowing hydrogen to be produced close to demand and thus minimising network conversion. This will also enable natural gas with post-combustion CCS to be used in industry and power generation. This will allow a more efficient use of natural and hydrogen and the existing networks.

Existing supply routes and markets for natural gas can continue to operate, providing efficient and competitive markets and ensuring security of supply, as they have done in the past.

Much will need to be done to secure a hydrogen based future including advances in technology, the development of a hydrogen supply chain and public acceptance. Policy will play a key role in advancing the hydrogen economy and we propose a number of measures to be considered.

Policy makers' role in securing a hydrogen future

Policy must play a significant role in achieving decarbonisation. Specifically it must enable industries to make the investments and adaptations necessary in order to develop a hydrogen energy economy. Accordingly, European and national policy makers will need to recognise the importance of hydrogen from natural gas in decarbonisation efforts and consider the following.

Policies that support the role of hydrogen in decarbonisation efforts and allow different technologies (including zero carbon gas) to compete on an equal basis should be developed to achieve the most efficient outcome.

Targets for zero carbon gas in the European energy mix should be set (including renewable gas from bio-sources and decarbonised gas), in order for investment in zero carbon gas options to become attractive and for innovation to progress.

Research into implementation of hydrogen technologies should be supported. These include fuel cells, hydrogen based fuels and methane pyrolysis methods, as well as uses for end use carbon products.

Investments in energy networks should be considered based on the impact of the investment on decarbonisation. The role of hydrogen from natural gas and the role of existing gas networks in enabling decarbonisation should be recognised, and research into converting natural gas networks to hydrogen should be supported. This should include demonstration projects from proof of concept towards implementation. Policy makers should ensure a level playing field for investments in infrastructure to support decarbonisation, whether it be the expansion of electricity grids or the conversion of natural gas grids.

ANNEX A – MODELLING APPROACH & GLOSSARY

A.1 Pöyry modelling overview

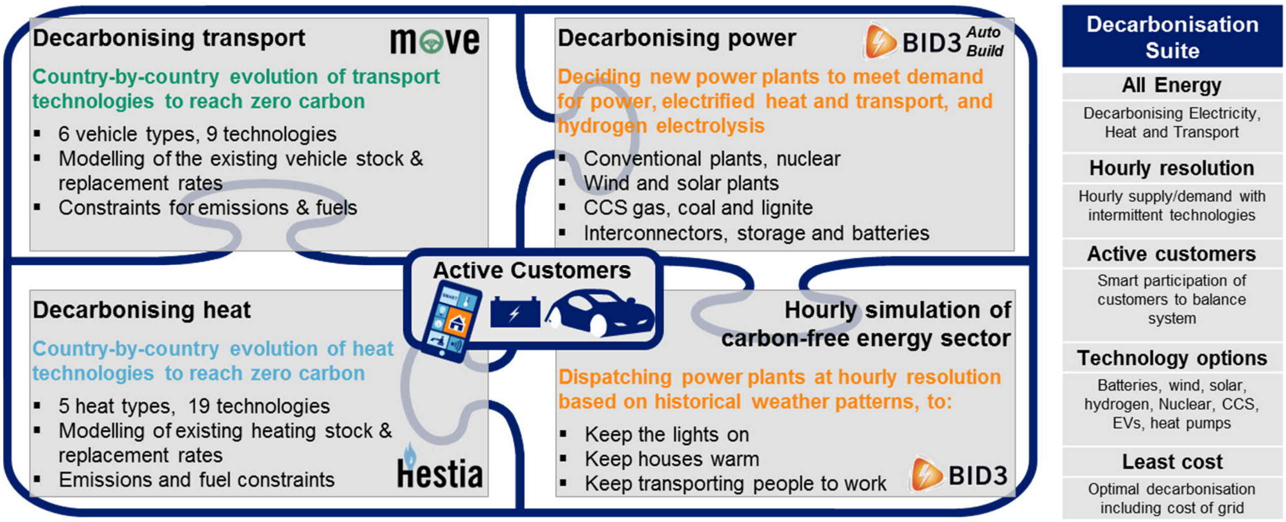
A.1.1 Modelling suite overview

Pöyry has developed an analytical framework to quantify the challenges of decarbonising the energy sector, using a suite of models to assess and compare decarbonisation pathways. This study investigates the decarbonisation of the energy sector, including power generation; residential, commercial, industrial and district heating; and land passenger and freight transport sectors. It does not include the non-combustion use of energy carriers such as gas or oil products used as feedstocks in industrial processes.

In order to estimate future capacities, output, and system costs, we use optimisation models for all sectors. Existing supply, scrapping rates and future demand are entered as inputs. The models then selects the optimal mix of new technologies, based on the need for new capacity, the cost and capabilities of the new capacities, including emissions, and deployment constraints, e.g. maximum amount commissioned in any year, and overall.

An overview of the model environment is presented in Figure 15.

Figure 15 – Pöyry's full decarbonisation modelling suite



In order to understand how future electricity supply and demand will interact it is critical to understand the flexibility of these demands, i.e. ability to shift demand away from peak periods or across a day, a week or a season. For all demand segments, transport, heat and residual, hourly demand profiles have been defined. A certain share of demand is defined as flexible, which means that BID3 can dynamically optimise the shifting of demand within this segment, within certain limits.

Hourly analysis of flexible demand is critical to calculating the total system costs for any specific scenario; otherwise the peak electricity may be over-estimated, extra peaking generation built, and alternative storage options developed when they would not actually have been required.

A.1.2 Transitioning heat and transport

For this study we have developed two new models, one for transport ('move') and one for heat ('Hestia'). These are capable of determining the future stock and output for transport and heat across Europe.

The transport and heat models are organised in similar ways, as they both provide outputs on an annual basis for future vehicle and heating stock numbers, heat generation or km output, as well as costs, fuel use and emissions. The transition towards a zero carbon system is modelled on the basis of the capabilities and costs of new technologies, as well as their availability, which is determined by supply chain constraints and political factors.

A.1.3 Power model – BID3

In the power sector modelling, we use our existing European market model, BID3. This model already includes key characteristics such as:

- **Plant parameters:** efficiencies/availability, risk of unexpected outages, time taken to ramp to full capacity, reduced efficiencies when ramping up and down more frequently.
- **Historical weather patterns**: application of historical weather patterns with hourly wind speeds, solar irradiation and temperatures being applied to future years to ensure an internally consistent temperature variance outcome on demand alongside actual levels of generation from wind and solar.
- **Security standards**: ensures that the power generation mix provides sufficient back-up for times when intermittent generation is very low.

For the purposes of this study we have further enhanced BID3 with two major features:

- **Flexibility of demand:** With the increase of smart meters and appliances, electric heating and electric vehicles, electricity demand is expected to become much more flexible. New flexible hourly demand profiles have been developed for end use of electricity for heat and transport, including the impact of temperature on heat pump efficiencies and electric vehicle ranges.
- **Hydrogen production:** The mix between the two alternatives of electrolysis and natural gas reforming are optimised both in the long-term (investment decisions) and short-term (dispatch). Electrolysis competes with the flexibility offered by electric vehicles and heating.

A.2 Key modelling inputs

A.2.1 Overview of key study assumptions

Table 4 provides an overview of those assumptions that are common across all investigated pathways, and those that change and therefore define the pathways.

Table 4 – Study assumptions – pathway comparison

	'All-Electric'	'Zero Carbon Gas'	'Zero Carbon Hydrogen'
Common assumptions	Population growth, GDP growth, sector contribution, settlement structure, weather patterns, technology development, commodity costs, energy efficiency, scrapping and refurbishment rates		
Pathway-specific assumptions			
Possibility to decarbonise fossil fuels	None	CCS (either in SMR/ATR or post-combustion in both power and heat)	CCS, pyrolysis
Availability of hydrogen	None	SMR/ATR with CCS, and electrolysis, from 2030	Same, plus pyrolysis, from 2030
Gas networks	Decommissioned	Retained, distribution converted to hydrogen	Retained, distribution converted to hydrogen
CO_2 network	None	Across Europe	Limited to North Sea

A.2.2 Underlying energy demand projections

Macro assumptions have been taken from the EU Reference Scenario 2016[29], reflecting the critical aim of delivering full decarbonisation without major behavioural changes and introducing inconsistencies between demand assumptions. Population and GDP grow moderately, sector contributions remaining largely flat.

Demand for heat was adapted from Fraunhofer's 'Mapping EU heat supply'[30] study from 2016. In the non-process heat sectors, space and water heating and cooling in buildings, demand declines over time, as

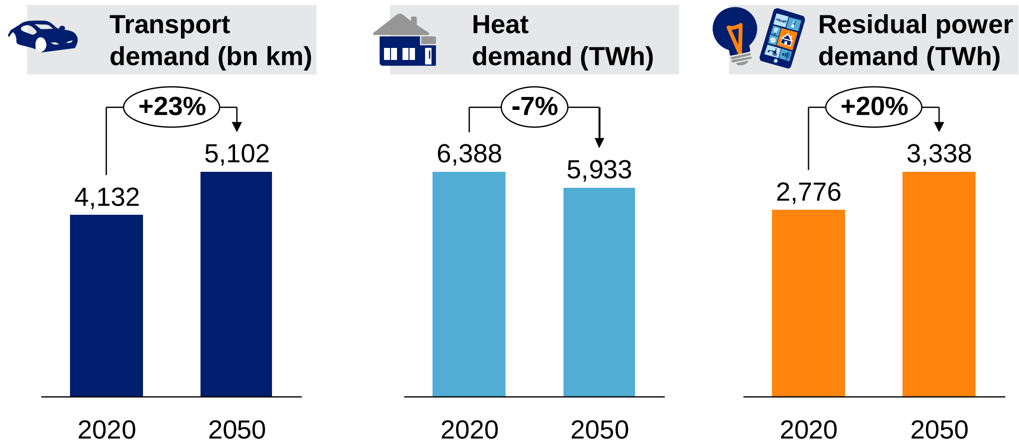
[29] European Commission. "EU Reference Scenario 2016. Energy, Transport & GHG Emissions Trends to 2050." 2016.

energy efficiency increases due to better building standards and insulation of existing buildings. In the process heat segment, output grows moderately, in line with GDP growth assumed in the EU reference case.

Residual power demand, which excludes demand from heat and transport, covers provision of lighting, and electric appliances (TVs, washing machines, fridges, etc.). This share of demand is projected to increase despite some improvement in appliance energy efficiency, as the number of electric appliances is expected to grow, especially in newer Member States.

Figure 16 provides an overview of the underlying demand assumptions.

Figure 16 – Demand assumptions



A.2.3 *Decarbonisation – the scale of the challenge*

Table 5 provides the breakdown of emissions across sectors of the economy. The focus of this paper is the 'energy sector', which, as defined in the study, comprises the first four elements of the table, power and large-scale heat, small-scale heat, industrial heat and transport.

Table 5 – Breakdown of emissions and target

	1990 (baseline)	2016		2050 target
Power & large-scale heat	1,442	1,027		
Small-scale heat	751	590		
Industrial heat	852	483		
Transport	812	960		
Industrial processes	536	387		
Other	1,359	945		
TOTAL	**5,751**	**4,393**		**288**

A.2.4 *Transport technology characteristics and costs*

In the transport sector, the existing road vehicle fleet data was obtained from Greek consultancy Emisia. Based on this data, our 'move' model splits the transport sector into segments based on fuel, size and use. For the rail sector it looks at the distances travelled for both passenger and freight transport.

The level of flexibility from EVs is a crucially important factor and for this study we assume private passenger EVs are only required to be fully charged on Mondays at 8am (equivalent to a weekly tank re-fuelling) whilst freight and public transport are required to be fully charged at 7am every morning.

30 Fraunhofer Institute for Systems and Innovation Research (ISI). "Mapping and analyses of the current and future (2020 - 2030) heating/cooling fuel deployment." 2016.

A.2.5 Heat technology characteristics and costs

The future deployment of heat technologies will depend on the relative efficiency, heat rate, capex, opex, appliance lifetimes and conversion costs (e.g. 'behind-the-meter' costs to allow air-source heat pumps to work in a wet heating environment or converting gas equipment to use hydrogen.

Deployment restrictions are applied in the modelling to reflect the time required to build supply chains for new technologies, e.g. limitations on number of heat pumps that can be deployed in each future decade.

In the 'Zero Carbon Gas' pathway[31] hybrid heat pumps are included. This provides a core level of heat via an air-source heat pump with additional heat from a boiler that uses natural gas, biomethane or hydrogen. When the ambient temperature drops below -10^{o}C all heat demand is met by the boiler.

A.2.6 Power technology characteristics and costs

Power generation cost assumptions to 2050 have been derived from external studies[32], with renewables reduced by a further 10% to reflect rapid reductions seen in auctions during 2017. We have ensured all technology build rates are within reasonable limits from a construction and supply chain perspective. Decisions to prohibit nuclear build in 12 countries have been respected.

A.2.7 Other costs

Prices for commodities that are being phased out in both pathways, such as coal, lignite or oil, are assumed to be flat at current levels (taken from the 2016 EU Reference Scenario). Gas prices are assumed to grow by 30%-40% until 2030, and then to remain flat in real terms, aligning with the IEA's 450 Scenario from the WEO 2016 for consistency with significant levels of global decarbonisation. Biomass prices also follow the same trajectory as gas.

Carbon prices have been initially set using values from the EU Reference Scenario. BID3 then produces the additional shadow price of carbon required to provide the price support necessary to meet not only the emissions limit but also investment hurdle rates.

Hydrogen production cost are based on a report produced for the Committee on Climate Change in the UK[33] with electrolysis costs decreasing by >35% until 2030, whereas methane reforming decreases more slowly. Our electricity modelling accounts for the production of hydrogen, using either electrolysis from power to gas (P2G) or reforming natural gas (which includes costs for the carbon capture and storage) using either steam reforming (SMR) or autothermal reforming (ATR).

The level of hydrogen produced from P2G depends on the amount of renewable production that makes economic sense to convert using electrolysis. The value that electrolysis can capture and its load factors will be influenced by the levels of demand side and other forms of flexibility, e.g. battery storage, that effectively competes with any excess renewable generation in both intra-day and longer timeframes.

Network costs, including both transmission and distribution, for electricity and natural gas are captured as new and replacement capex plus opex, are based on GB data and then adjusted to reflect individual countries' labour costs. For hydrogen networks we assume a 20% increase compared to gas for new build[34], or conversion capex if gas networks are converted to hydrogen[35].

Carbon capture and storage cost assumptions have been taken from the 'Electricity Generation Cost Report'[36], which includes both the cost of the plant, e.g. boiler or turbine, and the costs associated with CCS (capture, transport and storage).

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31 In the 'All-Electric' pathway, no zero carbon gases are available in 2050. Therefore, hybrid heat pumps are not available, since they would have no role in a fully decarbonised future.

32 BEIS, NERA, Arup, Leigh Fisher Jacobs, Energy Storage Update, BWE and VDMA

33 E4tech, UCL Energy Institute, and Kiwa Gastec."Scenarios for deployment of hydrogen in contributing to meeting carbon budgets and the 2050 target" 2015.

34 Dodds, Paul E., and Will McDowall. "A review of hydrogen delivery technologies for energy system models." 2012.

35 Northern Gas Networks, Kiwa Gastec, Amec Foster Wheeler, and Mike Haines. "H21 Leeds City Gate." 2018.

36 Leigh Fisher and Jacobs. "Electricity Generation Costs and Hurdle Rates." 2016.

A.3 Glossary

Term	Description
Biogas and biomethane	While biogas can contain a mix of gases produced from organic material, biomethane is much more pure and requires some upgrading of biogas. For the purpose of this paper, we do not make a strong distinction. We used the term biomethane for both but acknowledge that (1) biogas would not be injected into a grid without prior upgrading, and (2) not all appliances would be able to burn biogas without problems.
Biomass	Biomass is a term for organic matter used for energy production or in industrial processes. For the purpose of this paper, the term refers only to solid biomass (for gaseous fuels see biogas and biomethane)
Carbon black	Carbon black is pure carbon that can be produced from pyrolysis and used as a raw material for the production of other materials.
CCGT	Combined-cycle gas turbine
CCS	The term 'CCS' as it relates to the power and heat sectors in this paper, always refers to post-combustion CCS with natural gas. When used in the context of hydrogen production, it refers to methane reforming with CCS (see SMR with CCS below). We assume that the CO_2 is stored in storage sites in the North Sea, rather than used (CCUS). It should be noted, however, that we acknowledge the potential of solid carbon produced from pyrolysis to be used for other purposes.
Dispatchable generation	Dispatchable generation refers to sources of electricity that can turn their output up or down on demand and dispatched at the request of power grid operators, according to market or system needs. This is in contrast with non-dispatchable renewable energy sources such as wind and solar PV which can only be controlled to a very limited extent. The only types of renewable energy that are dispatchable without separate energy storage are hydroelectric, biomass, geothermal and ocean thermal energy conversion.
Energy sector	For the purpose of this paper, we define the energy sector as including power generation, heat production and ground-based transportation. Not included, among others, are aviation, waterborne transport and (non-combustion) industrial process emissions.
Flexible demand	Flexible demand is electricity demand that can be shifted from one period to another in a short-term context (hours to weeks) and therefore contribute to system stability and balancing. We assume that the majority of flexible demand will come from the transport sector, where electric vehicles can charge when a large amount of renewable electricity is available, rather than during peak hours.
Hybrid heat pump	Heating system in buildings, where the baseload heating is carried out by a heat pump, but during peak times (cold periods in winter), a boiler (using either natural gas, biomethane or hydrogen) would take over.
LCOE	The levelised cost of energy (LCOE), also known as Levelised Energy Cost (LEC), is the net present value of the unit-cost of energy over the lifetime of a generating asset. It is often taken as a proxy for the average price that the generating asset must receive in a market to break even over its lifetime.
OCGT	Open cycle gas turbine
Pyrolysis	Method to produce hydrogen from natural gas which produces hydrogen and sold carbon. The box in Section 1.4.2 provides additional detail on pyrolysis, and a high-level comparison with other hydrogen production methods is given in Section 1.4.1. Section 2.5 provides information about the role of pyrolysis as a technology to produce hydrogen within the context of the Zero Carbon Hydrogen pathway.
SMR with CCS	Steam methane reforming: technology to produce hydrogen from natural gas. Both steam methane reforming (SMR) and auto-thermal reforming (ATR) are potential processes of splitting methane into hydrogen and CO_2. For the purpose of this paper, we will use the term SMR, but no particular preference is indicated through this.
Zero carbon gas	Throughout this report, the term 'zero carbon gas' is used to refer to all gaseous fuels that have a zero carbon footprint, including hydrogen (produced from a zero carbon production method), CCS (where any residual CO_2-emissions from CCS are off-set by using biomethane, in the feedstock), biogas and biomethane.
Zero carbon hydrogen	Hydrogen produced via a zero carbon production method such as electrolysis using renewable electricity, SMR with CCS or methane pyrolysis.

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