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SYNERGY STUDY

HEAT RECOVERY FROM HYDROGEN PRODUCTION

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EXECUTIVE SUMMARY

Globally, it is increasingly recognised by governments and industry that hydrogen has an important role to play in delivering carbon emission reduction ambitions and supporting the transition to Net Zero.

In the UK, hydrogen has been identified by national and devolved governments as a credible key pathway for achieving Net Zero Targets. Indeed, the UK's Hydrogen Strategy[1] suggests that 250 – 460 TWh of hydrogen could be needed by 2050, making up 20 – 35% of the UK's final energy consumption. The primary role of this hydrogen would be to replace (or extensively displace) natural gas in parts of the energy system, and / or to act as an energy storage medium.

In the context of this study, only low / zero carbon hydrogen is considered, and in the current landscape, the associated hydrogen production processes comprise:

- Green hydrogen production (Electrolysis with renewable electricity); and,
- Blue hydrogen production (Steam hydrocarbon (methane) reformation coupled with carbon capture).

Such hydrogen production produces very substantial quantities of waste heat and, to date, very little attention has been given to this significant by-product, and the opportunities it presents if captured and utilised.

This study seeks to address this knowledge gap, and the scale thereof.

Indeed, as the scale of hydrogen production infrastructure grows, the quantity of available waste heat will also grow.

This presents substantial opportunities, including the decarbonisation of both existing and new district heating networks, with associated opportunities to:

- Increase energy efficiency and revenue to hydrogen producers; and,
- Increase the availability of low cost, low carbon waste heat for heat users and suppliers (e.g. district heat network operators).

In terms of increasing the availability of low cost, low carbon waste heat for heat users, it has been estimated that by 2050 the quantity of waste heat arising as by-product of hydrogen production could be between 31 to 144 TWh[2].

This is equivalent to:

- *Up to 131% of the UK domestic space heating demand[3]; and,*
- *Up to 27% of the total UK heating demand[4].*

Further, the literature review indicated that recovering waste heat from some hydrogen production processes (particularly green hydrogen production) should not have any negative impact on process efficiency. Indeed, various literature sources suggest that *the system efficiency of electrolyser plants can increase by 14 to 32% by recovering waste heat*.

This directly contradicts the opinion that hydrogen production and heat networks are in competition with each other, and these observations suggest there are clear and potentially very significant synergies between the hydrogen and heat sectors.

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[1] 'UK Hydrogen Strategy' (Department for Business, Energy and Industrial Strategy, 17 August 2021). Available online at: https://www.gov.uk/government/publications/uk-hydrogen-strategy

[2] Based on the UK's Hydrogen Strategy projection of 250 – 460 TWh of hydrogen by 2050, and assuming a production efficiency of 80%, and a heat loss between 10 – 25% of input energy.

[3] Assuming UK domestic space heating demand between 110 – 250 TWh (to achieve Net Zero Targets). Source: 'Future Energy Scenarios' (National Grid, July 2021). Available at: https://www.nationalgrideso.com/future-energy/future-energy-scenarios/fes-2021/documents

[4] Assuming total UK heating demand of 540 TWh. Source: 'Opportunity Areas for District Heating Networks in the UK: National Comprehensive Assessment of the Potential for Efficient Heating and Cooling'. (Department for Business, Energy and Industrial Strategy, September 2021). Available at: https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/1015585/opps_for_dhnnca_hc.pdf

An exploration of these synergies provided the focus for this study and involved the identification of waste heat streams arising from any hydrogen production process, and capture and utilisation of this heat within adjacent heat networks. Noting the hydrogen production processes, the study focussed on several identified 'cluster' areas where both the hydrogen and heat sectors are understood to be rapidly evolving in tandem. These areas comprised:

- Aberdeen City;
- Leeds City; and,
- The Humber Region (split into Beverley, Hull and South Humber).

Across each cluster, planned and potential hydrogen production and district heating network developments were identified and mapped.

Subsequently, a technical assessment was undertaken to shortlist a single preferred synergy opportunity to be taken forward into an economic assessment, with the economic assessment undertaken to determine the associated viability of the shortlisted synergy opportunity.

Within the technical assessment screening, the following criteria were applied: waste heat availability; heat demand; proximity / distance of hydrogen production to district heat network; heat quality (heat temperature); hydrogen production growth potential; district heating network growth potential; level of stakeholder interest; timescale to implementation; and, transferability.

Based on the technical assessment, South Humber (from the Humber Region) was selected as the preferred synergy to be taken forward for the economic modelling and assessment. This synergy presents three hydrogen projects planned in close proximity; two very substantial (2 x 100MW) green hydrogen projects, and another large (700 MW) blue hydrogen project. In addition, within the South Humber region, there are also several potential heat networks which have been subject to previous feasibility studies, and identified as potentially viable.

Based on the economic assessment, the Table provides a summary of the impacts of waste heat recovery for the South Humber synergy.

Table: SUMMARY OF THE IMPACTS OF WASTE HEAT RECOVERY FOR THE SOUTH HUMBER SYNERGY

	Hydrogen Production	District Heating Network
Technical	• Improved system efficiency • Reduced auxiliary power consumption • Minimal modification requirements to the plant • Additional space requirements	• Improved efficiency of heat supply equipment • Reduced energy consumption • Additional network infrastructure requirements • Additional thermal storage and controls requirements
Commercial	• Additional revenue streams and savings • Enhanced business case • Improved revenues from hydrogen sales	• Additional capital costs • Lower operating costs • Enhanced business case • Reduced cost to the consumers
Environmental	• Reduced carbon emissions	• Carbon savings • Air quality cost benefits

The economic assessment was performed for a green hydrogen project. However, the synergy concept is also applicable for the blue hydrogen projects.

A main conclusion from the economic assessment is that it is technically feasible to recover waste heat from hydrogen production without negatively impacting the production, and that it is economically attractive to utilise this waste heat to supply district heating networks compared to the counterfactual scenario using air source heat pumps.

In particular, noting the selected South Humber synergy and the associated economic modelling, there is a technically and economically feasible project opportunity.

For the South Humber synergy, the economic assessment also noted that the project presented an attractive business case for both the hydrogen production and district heat network operators, with following key financial results:

- For the hydrogen production operator: Projected IRR of 14%, with a positive NPV.
- For the district neat network operator: Projected IRR of >4%, with positive NPV (compared with counterfactual scenario projected IRR of <1% IRR).

Additionally, in comparison with the counterfactual scenario using air source heat pumps, the South Humber synergy could:

- Reduce the heating cost to the consumers by approximately 20%; and,
- Reduce carbon emissions by over 50%.

The sensitivity assessment suggested that the success of the project is highly dependent on the following factors:

- *High Heat Demand and Availability of Waste Heat:*
  The project is highly sensitive to the availability of waste heat and heat demand. Therefore, the sufficient availability of waste heat and heat load is critical to make the project feasible.
- *Capital Cost:*
  The project is also very sensitive to the initial capital cost. Consequently, following enablers are identified to minimise the initial capital investment:
  - Waste heat temperature higher than the network operating temperature;
  - Lower network operating temperatures (e.g. for new developments and more efficient heating systems);
  - Close proximity of hydrogen projects from heat clusters; and,
  - Availability of grant funding.
- *Heat Sale Rate:*
  Heat sale rate will also have a significant impact on the project performance. In most cases, the heat sale rate will depend on the availability of other low-cost heat alternatives and hence the early assessment of other alternatives and the strategic placement of the project is crucial.

The overarching conclusion of this Study is that significant economic, environmental and social benefits are associated with heat recovery from hydrogen production, and its auxiliary processes.

However, for such benefits to be realised, hydrogen production projects would have to be placed in close proximity to heat clusters. This not only provides an opportunity to develop local clean sources of hydrogen (with the potential to attract new businesses to the area), but also forms a key part of the decarbonisation of energy, and could significantly accelerate the UK's decarbonisation of heat.

The main recommendation, given the significant environmental, economic and social benefits, is to carry out further and more detailed assessment of the synergy opportunities identified.

1 INTRODUCTION

1.1 Background

Globally, it is increasingly recognised by governments and industry that hydrogen has an important role to play in delivering carbon emission reduction ambitions and supporting the transition to Net Zero.

In the UK, hydrogen has been identified by national and devolved governments as a credible key pathway for achieving Net Zero Targets[5]. Indeed, the UK's Hydrogen Strategy[6] suggests that 250 – 460 TWh of hydrogen could be needed by 2050, making up 20 – 35% of the UK's final energy consumption. Recent analysis[7] has suggested that the primary role of this hydrogen would be to:

- Replace (or extensively displace) natural gas in parts of the energy system where electrification is not feasible / is prohibitively expensive[8]; and / or,
- Act as an energy storage medium[9].

The current focus of UK hydrogen policy, and associated research and development, has been on these two key areas.

However, such hydrogen production also produces very substantial quantities of waste heat and, to date, very little attention has been given to this significant by-product, and the opportunities it presents if captured and utilised.

This study seeks to address this knowledge gap, and the scale thereof.

Indeed, as the scale of hydrogen production infrastructure grows, the quantity of available waste heat will also grow. This presents substantial opportunities, including the decarbonisation of both existing and new district heating networks, with associated opportunities to:

- Increase energy efficiency and revenue to hydrogen producers; and,
- Increase the availability of low cost, low carbon waste heat for heat users and suppliers (e.g. district heat network operators).

To put the latter into context, it has been estimated that by 2050 the quantity of waste heat arising as a by-product of hydrogen production could be between 31 to 144 TWh[10].

This is equivalent to:

- Between 13 to 131% of the UK domestic space heating demand[11]; and,
- Between 6 to 27% of the total UK heating demand[12].

This directly contradicts the opinion that hydrogen production and heat networks are in competition with each other, and these observations suggest there are clear and potentially very significant synergies between the hydrogen and heat sectors.

An exploration of these synergies provided the focus for this study, which required strategic assessment of potential synergies, taking account of existing, planned and potential future

[5] The UK Government's 2050 'Net Zero' Target, set via the 2019 amendment to the 2008 Climate Change Act, requires a 100% reduction of all greenhouse gas emissions compared with 1990 levels. The original 2008 Climate Change Act required an 80% reduction of all greenhouse gas emissions compared with 1990 levels. Amended 2008 Climate Change Act available at: https://www.legislation.gov.uk/ukpga/2008/27/contents

[6] 'UK Hydrogen Strategy' (Department for Business, Energy and Industrial Strategy, 17 August 2021). Available online at: https://www.gov.uk/government/publications/uk-hydrogen-strategy

[7] For example: 'Hydrogen in a Low Carbon Economy' (Committee on Climate Change, November 2018). Available at: https://www.theccc.org.uk/publication/hydrogen-in-a-low-carbon-economy/

[8] For example: in back-up power generation; in industrial heat processes; and / or, in providing heat on cold winter days.

[9] For example: to provide balancing for intermittent renewable power sources such as solar PV / wind when demand on the grid is low.

[10] Based on the UK's Hydrogen Strategy projection of 250 – 460 TWh of hydrogen by 2050, and assuming a production efficiency of 80%, and a heat loss between 10 – 25% of input energy.

[11] Assuming UK domestic space heating demand between 110 – 250 TWh (to achieve Net Zero Targets). Source: 'Future Energy Scenarios' (National Grid, July 2021). Available at: https://www.nationalgrideso.com/future-energy/future-energy-scenarios/fes-2021/documents

[12] Assuming total UK heating demand of 540 TWh. Source: 'Opportunity Areas for District Heating Networks in the UK: National Comprehensive Assessment of the Potential for Efficient Heating and Cooling'. (Department for Business, Energy and Industrial Strategy, September 2021). Available at: https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/1015585/opps_for_dhnnca_hc.pdf

infrastructure. The study gave particular focus on several identified 'cluster' areas where both the hydrogen and heat sectors are understood to be rapidly evolving in tandem.

1.2 Objectives

In March 2021, Ramboll Energy was appointed by the Embassy of Denmark to undertake a study assessing the potential synergies between future hydrogen production and associated waste heat recovery for the use in district heating / heat network applications.

The key objectives of the study were as follows:

- Create a Vision and Associated Narrative for Waste Heat Recovery from Hydrogen Production.

  Noting the proposed development of hydrogen production projects / industrial clusters, the study aimed to provide UK Government, planning authorities and project stakeholders with a vision and narrative for engaging with and promoting hydrogen-driven heat planning opportunities.

- Highlight Potential Investment Opportunities for both Hydrogen and District Heating / Heat Network Investors.

  The study also aimed to highlight attractive immediate and future investment opportunities arising from synergies between hydrogen, waste heat recovery and low carbon heat supply.

- Re-Capture and Solidify Wider Interest in Waste Heat Recovery

  Noting the political momentum for the development of a UK hydrogen economy, the study also aimed to re-capture and solidify wider interest in waste heat recovery from industry as a means of support heat decarbonisation, while also commenting on the current policy barriers and potential enablers surrounding this approach.

Building on inspiration from Europe, and in particular Denmark, the study focussed on the UK context, based on an ambitious national programme for developing both hydrogen and district heating infrastructure.

2 BACKGROUND

2.1 Overview

This Section provides technical background on hydrogen production processes and the associated waste heat recovery potential.

2.2 The Synergy Concept

Noting the UK Government's Net Zero Target there is an increasing focus on hydrogen as an energy carrier to support decarbonisation of the UK energy system. Where there is high potential growth (i.e. new hydrogen production infrastructure) there is also an opportunity for a change in thinking to harness new technology in the most resource efficient way. When the focus of effort is on the development and optimisation of a new process facility it is often the case that a demarcation is drawn around the new process and the desired output- in this case the hydrogen production facility and the hydrogen product. However, it is often the case that other by-products are present that can be useful to and present synergies with other nearby users. Finding users for by-products of production is not always straightforward and can detract developers' attention away from the core project. Conversely, those synergies can ultimately add to the profitability of the project and support a stronger business case.

The exploration of the synergy concept in this study involves the identification of waste heat streams arising from any hydrogen production process, and capture and utilisation of this heat within adjacent heat networks. The concept aims to set out the vision and associated narrative for hydrogen-derived waste heat utilisation, to support planning for and decarbonising UK heat networks.

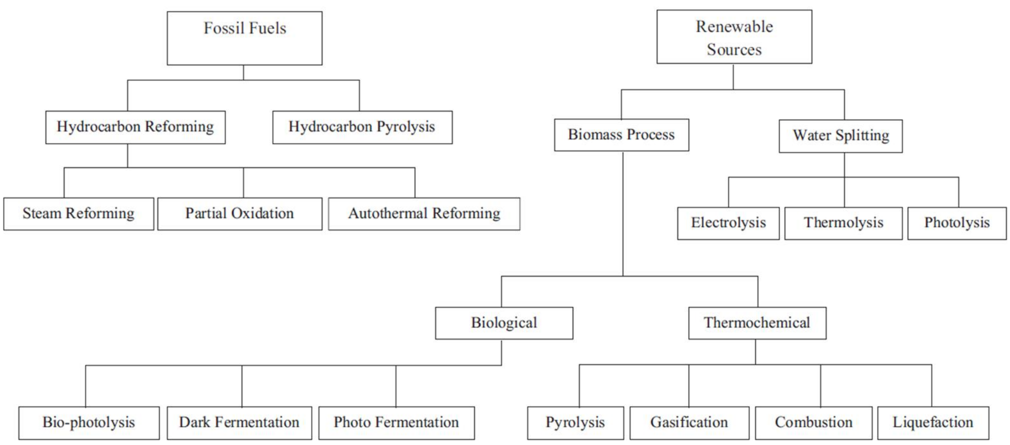
2.3 Hydrogen Production Processes

Hydrogen is one of the most abundant elements in the universe. However, it is rare in the earth's atmosphere, in its pure form, H_2, and rather is usually bonded to other elements, for example as water (H_2O) or as hydrocarbons (such as methane (CH_4)). Therefore, hydrogen production processes traditionally involve taking a compound containing the element itself and removing other elements to produce a pure hydrogen product. By-products are therefore also produced, such as (where hydrogen is removed from water) O_2 and waste heat.

Before considering the nature and quantity of waste heat available from different hydrogen production techniques, it is important to understand some of the basics with regards to different forms of hydrogen production.

Figure 2-1 illustrates that hydrogen production can take many different forms, with each process presenting different efficiencies, rates and yields of hydrogen, its own advantages and disadvantages.

Figure 2-1: HYDROGEN PRODUCTION PROCESSES (Nikolaidis and Poullikkas 2017)



In the context of this study, only the low / zero carbon hydrogen production processes are considered as viable forms of hydrogen production. In the current landscape, these hydrogen production processes comprise:

- Green hydrogen production (Electrolysis with renewable electricity); and,
- Blue hydrogen production (Steam hydrocarbon (methane) reformation coupled with carbon capture).

Therefore, this study focuses these two processes and the associated waste heat.

2.3.1 Green Hydrogen Production (Electrolysis)

In electrolysis, water (H_2O) is split into hydrogen (H_2) and oxygen (O_2) by using electricity.

As the feedstock is water, the process itself produces no carbon. As such, the carbon factor of the hydrogen produced is determined by the carbon content of the electricity used. Though the UK grid is rapidly decarbonising, for genuine green hydrogen production, the electricity required should be sourced solely from renewable electricity sources, and hence the resultant hydrogen will have zero carbon content. In the geographies investigated within this study the most common form of renewable power available is wind power.

One way to ensure renewable power is used for the process is to build the electrolyser near the renewable energy source, or associated transmission infrastructure. In the case of offshore wind, this could be the land-based substation that the wind turbines feed into, or the wind generation facility itself. A private wire arrangement could be used to power the hydrogen production with cheaper renewable power when grid demand is low.

Different electrolyser technologies exist, currently categorised into three main types:

- PEM (proton exchange membrane);
- Alkaline (Atmospheric and Pressurised); and,
- Solid oxide.

PEM and alkaline electrolysers are commercially available today.

Solid oxide electrolysers operate at relatively high temperature (700 – 1000°C) and have high conversion efficiency. They can also potentially produce syngas along with hydrogen. Solid Oxide electrolysers are still in the development stage.

Each type of electrolyser has unique operating parameters and configuration. For example, PEM and pressurised alkaline electrolyser both have the advantage of quickly reacting to variations in power supply, typical of renewable power sources. This in and of itself can be an advantage in maximising the yield and utilisation of renewable power sources, particularly within the context of an increasingly constrained National Grid.

2.3.2 Blue Hydrogen Production (Steam Methane Reformation coupled with Carbon Capture)

While blue hydrogen has some similarities to the above, it is a very different process and the typical scale of application as much larger. The core process in blue hydrogen production is Steam Methane Reformation (SMR). In SMR, a hydrocarbon feedstock, typically in the form of natural gas, reacts with steam to produce hydrogen. The reaction takes place at the temperature range of 700 – 900°C or higher, and in the presence of a catalyst (ruthenium, rhodium, palladium and platinum with nickel on aluminium oxide (Al_2O_3) or magnesium oxide (MgO) as carrier). Carbon emissions are produced from the core process itself, as well as from the generation of heat. SMR is very well-established technology and this process is highly optimised in terms of the waste heat recovery.

To classify as blue hydrogen, the process also includes carbon capture and associated carbon storage.

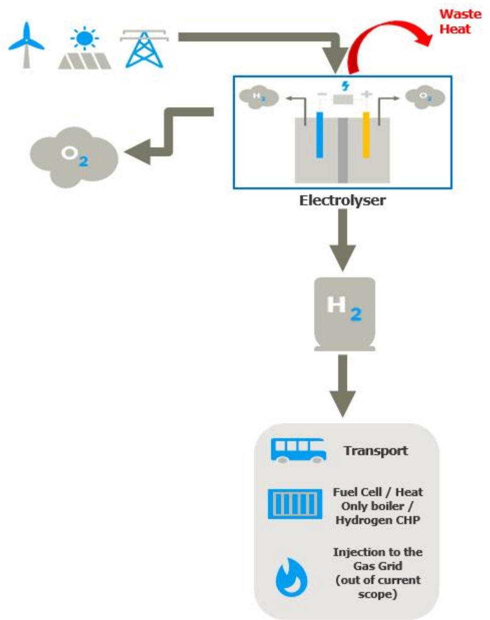
2.4 Waste Heat from Hydrogen Production

2.4.1 Green Hydrogen

Electrolysis is not 100% efficient, and a portion of the electricity supplied to the process ends up as waste heat. Depending on the type and design of electrolyser the quantity of this waste heat varies between 17 – 22% of the input energy. The temperature of the waste heat also varies depending on the electrolyser selected. The range of waste heat temperatures for typical electrolysers can vary anywhere between 40 – 80°C, largely driven by each manufacturer's specific cooling water requirements.

Figure 2-2 presents a simplified overview of the green hydrogen production process.

Figure 2-2: GREEN HYDROGEN PRODUCTION PROCESS



Electrolyser cooling water is used to maintain the electrolyser operating temperature below the design limit. The cooling water circuit is hydraulically separated from electrolyser circuit.

The cooling water continually extracts the waste heat from electrolysis, rejecting it to the atmosphere through a cooling system such as a dry air cooler, or a cooling tower. The cooling water is then returned to the electrolyser.

Recovering heat from this configuration would be relatively straight forward and the amount of equipment needed to do so would depend on the cooling temperature requirements of the electrolyser and the specific heat offtake requirements (e.g. district heating network flow temperature requirements). In general, higher electrolyser operating temperatures combined with lower district heating network temperatures will mean less equipment would be needed for the heat to be utilised to its full potential.

2.4.2 Blue Hydrogen

The reaction in the SMR process is 'endothermic', that is it requires an external heat source / input. The heat for SMR is required at between 700 – 900°C and typically produced by combustion of fossil fuels. Over the years SMR technology has been optimised to maximise recovery of the waste heat arising from the initial combustion process. This heat is typically recovered in the form of steam and hot water. Therefore, the potential for recovering heat from the core SMR process for applications such as district heating is likely to be limited and should be assessed on a case-by-case basis.

However, blue hydrogen production also has many auxiliary processes (such as carbon capture, and associated compression, etc) which need cooling and often these are serviced by a common cooling water system. It normally makes economic sense to collect these heat loads together and cool them in one or a series of cooling towers where the heat from auxiliary processes is released to the atmosphere. This heat can be captured and used for useful applications such as heat networks.

Typical cooling water flow and return temperatures vary depending on climate and environment but flow temperatures of around 30 – 35°C are typical. With waste heat temperatures in the lower end of heat quality range (30°C), additional equipment such as heat pumps will be needed to elevate the temperature for use in a district heating network.

With the complexity of the blue hydrogen production process, the likelihood is that a larger plant of this type is built due to the complexities of its operation and economies of scale. This would mean that a large quantity of waste heat from auxiliary processes would be available due to the plant size.

2.5 European Case Studies (Rotterdam / Denmark)

The synergy concept is not new, and several large-scale hydrogen projects under development already have plans to develop a similar approach. The following provides details of European case studies for projects currently under development.

2.5.1 Rotterdam[13]

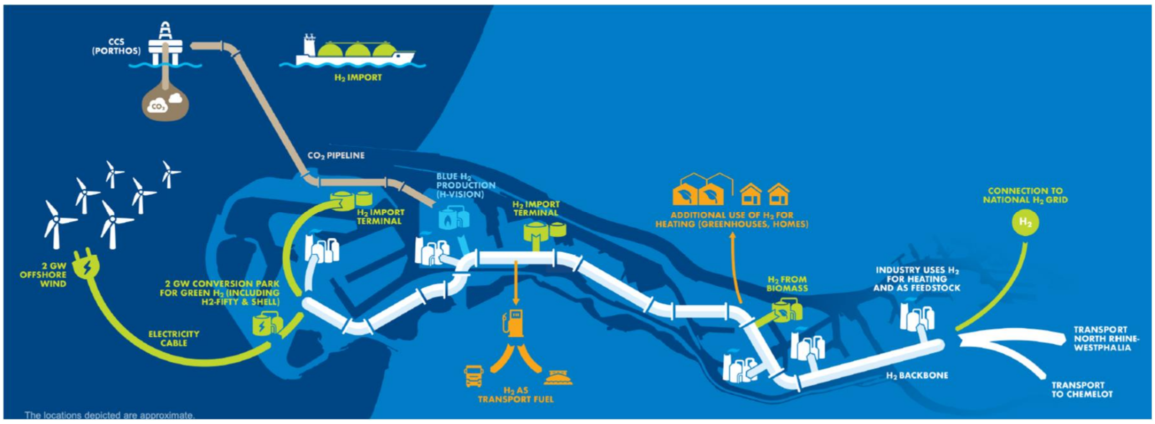
The Port of Rotterdam is a major European hub for the import of many products to the Netherlands and other European nations. The port currently imports a high proportion of the fuels and chemical feedstocks used by industry across the Netherlands and Germany. The Netherlands is also developing offshore wind at scale.

The Port of Rotterdam is developing multiple hydrogen projects and infrastructure in the Rotterdam area with a vision to extend production beyond its shores and develop a hydrogen import terminal to support future growth of the hydrogen economy.

The plan is to install a hydrogen 'backbone' at the port which interlinks hydrogen production, import and storage across multiple projects. A major hydrogen pipeline will be developed – in Rotterdam the pipeline will be a new build, with the connection to the industrial regions in the Netherlands based on re-purposing the existing natural gas grids (by Gasunie). The hydrogen pipeline in Rotterdam is due to become operational as early as 2024.

Figure 2-3 presents information on the hydrogen pipeline at the Port of Rotterdam[14].

Figure 2-3: VISUAL INFORMATION ON THE HYDROGEN PIPELINE AT THE PORT OF ROTTERDAM



A core element of the project is the development of a 2 GW 'Conversion Park' for green hydrogen production. The Park will have 2 GW of offshore wind capacity linked directly to hydrogen production plant. The first installations of 150 – 250 MW electrolyser capacity is expected by 2023, and the second 250 MW electrolyser project in 2025. This will provide an excellent opportunity for waste heat recovery.

The port authority has plans to harness the waste heat arising from the electrolysers by installing new and connecting existing district heating infrastructure, exploiting waste heat on a grand scale, including plans to supply up to half a million households by 2030. This gives the opportunity for hydrogen producers to sell heat into the heat network, rather than vent to the atmosphere, creating an important additional revenue stream.

The Port's plans also include development of blue hydrogen production as a temporary replacement fuel for the power generation and petrochemical industry located in the area, with the CO_2

[13] Based on information on: 'Hydrogen in Rotterdam'. Available at: https://www.portofrotterdam.com/en/port-future/energy-transition/ongoing-projects/hydrogen-rotterdam
[14] Visual information taken from 'Hydrogen Economy in Rotterdam' (as Handout). Available at: https://www.portofrotterdam.com/sites/default/files/2021-06/hydrogen-economy-in-rotterdam-handout.pdf

produced being curtailed in CCS and also used in local green housing operations. This blue hydrogen production presents further opportunities to recover waste heat.

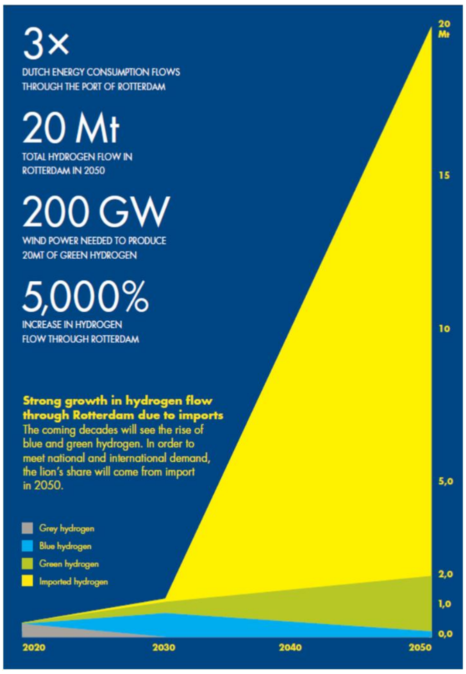
Figure 2-4 presents visual information on the district heating plans at the Port of Rotterdam[15].

Figure 2-4: VISUAL INFORMATION ON THE DISTRICT HEATING PLANS AT THE PORT OF ROTTERDAM

The scale of hydrogen production in this case is vast by any standards; however, the quantity of hydrogen demand is substantially higher than (10 times) the total production capacity which can be installed due to spatial constraints. Therefore much of the hydrogen will need to be imported from locations which have high wind and solar power capacity.

Figure 2-5 presents the proposed import versus hydrogen production capacity at the Port of Rotterdam[16].

Figure 2-5: IMPORT VERSUS HYDROGEN PRODUCTION (PORT OF ROTTERDAM)



The potential hydrogen demand estimates for Rotterdam suggest that there will be significant waste heat generated as a result of local supply to this demand. A heat network is being developed to transport waste heat from the Port (not only from electrolysers, but also from a refinery and other sources) to commercial green houses in Hauge and the horticulture business in

[15] Visual information taken from 'Heat Recovery from Hydrogen Production' (Randolf Weterings Synergy Study Final Webinar Presentation, September 2021).

[16] Visual information taken from 'Hydrogen Economy in Rotterdam' (as Handout). Available at: https://www.portofrotterdam.com/sites/default/files/2021-06/hydrogen-economy-in-rotterdam-handout.pdf

Westland. In future there is an ambition to expand this heat network to connect additional residential and commercial heat loads.

2.5.2 Denmark[17]

The Danish district heating sector is very well-established, with 61% of the country's space heating demand currently supplied though district heating networks.

The Danish district heating association commissioned a study ('Power-To-X and District Heating') which investigated some of the factors underpinning decision-making related to green hydrogen production and the use of waste heat for district heating.

Table 2-1 summarises details from some of the case studies covered by the study, including some of the key takeaways.

Table 2-1: DANISH POWER-TO-X CASE STUDIES AND KEY TAKEAWAYS

Where	Project	Partners	Capacity	Year (Operation)	Heat Recovery
Esbjerg	Green hydrogen and ammonium production (for agriculture and shipping)	Copenhagen Infrastructure Partners, Arla, Danish Crown, DLG, Mærsk, DFDS	1 GW	2026	Yes
Copenhagen	'Green Fuels for Denmark' comprising green hydrogen including carbon capture (from other point source) for fuel production	Ørsted, CPH Airport, Mærsk, DSV, SAS	10 MW (demo)	2023	Yes
			250 MW	2027	
			1.3 GW	2030	
Fredericia	HySynergy - Green hydrogen to replace fossil hydrogen	Everfuel, Shell (now Postlane Partners), TVIS,	20 MW	2022	Yes
			300 MW	2024	
			1 GW	2030	

2.5.2.1 Esbjerg

Esbjerg is a seaport town on the west coast of Denmark. It is the fifth largest city in Denmark and is known as an energy port due to its links with the oil and gas sector. In recent years it has become a world leading port for offshore wind, exporting 67% of offshore wind turbines installed across the EU.

Esbjerg is in the process of phasing out the 350 MW coal-fired power plant which supplies the local district heating network. The plant is being replaced with 50 MW of marine-source heat pumps and 60 MW of biomass (wood chip) boiler capacity, with the remaining capacity to be supplied by electrolyser waste heat.

Esbjerg is located close to many offshore wind projects and so is well placed to benefit from the renewable energy needed for green hydrogen production.

Esbjerg has plans to develop up to 1 GW of electrolyser plant for the world's largest green ammonia plant; the waste heat from this plant is estimated to be capable of covering a third of the total heat demand across the local district heating networks. This project has the potential to reduce CO_2 emissions associated with the existing district heating networks heat supply by 1.5 million tonnes per annum, creating 100 – 150 new permeant jobs.

[17] Based on information within: 'Power to X and District Heating' (DANSK FJERNVARME, GRON ENERGI, COWI, TVIS).

2.5.2.2 Copenhagen

‘Green fuels for Denmark’ is a project partnership to develop green fuels for road, maritime and air transport in three phases.

The first demonstrator phase is based on a 10 MW electrolyser to provide hydrogen for direct use in buses and heavy good vehicles.

The second phase will involve 250 MW of electrolysers and carbon captured from CCUS projects in greater Copenhagen to produce green methanol and aviation fuel.

The third phase is for 1.3 GW of electrolyser capacity for the total production of 250,000 tonnes green fuels.

The use of waste heat from these hydrogen projects across the greater Copenhagen area complex, and plans are being investigated by several organisations in collaboration with local district heating companies, and through wider collaborations across various industry sectors and municipalities.

2.5.2.3 Fredericia

Frederica, Kolding and Vejle are three industrial areas of Denmark that have worked together to collaborate and coordinate on strategic infrastructure developments since the 1960’s. A recent development in 2018 saw the conversion of a power plant (Skærbæk) to run on wood chips rather than natural gas. This was the start of a shift away from fossil fuels and further development has seen development of the use of waste heat from a local energy-from-waste plant.

There are now plans for additional waste heat to be recovered from a new electrolyser plant in and around this existing district heating network.

The afore-mentioned study further highlighted that early involvement of all stakeholders is key to making all of these heat recovery projects feasible. The study also modelled case studies based on different sizes of green hydrogen plants (20 MW and 400 MW). This showed an increase in revenue resulting from heat recovery and supply into the heat network, accruing to both additional hydrogen production as well as sale of low carbon heat. This was because a connection to the heat network would allow the hydrogen plant to run more continuously.

2.5.3 Conclusions from Case Studies

- Many current / imminent large-scale hydrogen production projects in Europe are actively developing waste heat recovery and utilisation as part of their overall business model.
- Existing heat networks are playing an important enabling role in supporting the development of hydrogen production planning in Denmark.
- Early engagement and involvement of key stakeholders is key to developing technically and financially viable hydrogen-driven waste heat recovery projects.
- In areas where the heat grid is complex, such as Copenhagen, the opportunity of waste heat from large electrolyser projects can offer a great opportunity to both the hydrogen project and district heating network operators.
- The case studies discussed here suggest that the synergy concept that is the subject of this report will improve the economics of hydrogen production and generate important cost-efficiencies and decarbonisation benefits for heat network operators.

2.6 Previous Ramboll Studies

In 2020, Ramboll was appointed by Danish Energy Agency (DEA) to qualify the current understanding of the potential for and limitation of hydrogen for heating, and especially in relation to district heating. A list of questions were developed in combination with the DEA. These were grouped under the following headings:

(1) Future Demand and Constraints on the Supply of Hydrogen.

(2) Waste Heat Utilization and District Heating in relation to Hydrogen.

(3) Distribution and Consumption of Hydrogen for Heating in Households.

The questions were addressed through a literature review of available reports. The study was focused on the UK, Germany and Dutch programs, but primarily on the UK.

The key conclusions were as follows:

- Future Demand and Constraints on the Supply of Hydrogen

  If all expected offshore wind capacity in 2050 was used to produce green hydrogen, and twice as much blue hydrogen was produced, this could cover the fossil fuel-based energy demand of the industrial sector and the heavy transport sector. This amount of hydrogen (which still excludes compression, transmission and hydrogen-to-end-use conversion losses) corresponds to only 32% of the total EU28 final energy (2018).

  This indicates that hydrogen use is likely to be constrained too hard-to-decarbonise sectors, such as heavy industries requiring high-grade heat.

- Waste Heat Utilization and District Heating in relation to Hydrogen

  Utilisation of waste heat through DH networks is likely to be an interesting business case for both the heat network operators and hydrogen producers. Economic feasibility will need to be assessed on a case-to-case basis.

- Distribution and Consumption of Hydrogen directly for Heating in Households

  Heat pumps or direct electric heating are likely to be a more efficient use of renewable electricity for heating, by factors of 5 and 1.3, respectively, compared to converting that electricity to hydrogen for direct combustion in a boiler.

3 SCOPE AND METHODOLOGY

3.1 Overview

This Section provides a summary of the overall scope and methodology.

Further details of the specific approaches adopted, and findings arising from each task, are then described in more detail in the associated Sections.

3.2 Literature Review

In addition to the above case studies, Ramboll appointed Newcastle University to conduct a literature review to investigate waste heat recovery from hydrogen production potential.

The literature review considered the UK's current hydrogen production and district heat network landscape, hydrogen production and storage processes, and low-carbon hydrogen and heat economics (considering both waste heat from hydrogen production and direct use of hydrogen).

The literature review also sought to identify UK hydrogen production projects.

Section 4 (Literature Review) presents further information on the Newcastle University literature review, alongside wider background information on hydrogen production, and waste heat recovery from hydrogen production. Appendix A provides the Literature Review report.

3.3 Synergy Opportunity Assessment & Mapping

In addition to the case studies and literature review, the study incorporated extensive stakeholder engagement to identify synergy opportunities across three specific 'clusters' locations comprising:

- Aberdeen City;
- Leeds City; and,
- The Humber Region.

Across each cluster, planned and potential hydrogen production and district heating network developments were identified and mapped.

Key hydrogen production and district heat network project details, and associated stakeholder contacts, within each of the three clusters were assimilated. The primary focus was on existing and planned projects that have a sufficient extent and quality of technical data / information available for the technical (and economic) assessment. However, noting the study's strategic focus, additional focus was given to potential future projects, and any associated potential synergies.

To support this, the identified stakeholders for individual projects in each cluster were consulted for further data / information, focussing on:

- For hydrogen projection projects: location; hydrogen production technology and capacity; programme / timeline;
- For existing and proposed district heat networks: location of any central plant; heat demand / proposed heat sources; layout / location of any network; programme / timeline; and,
- Local planning information and spatial strategies.

Additional (non-project-specific) stakeholders were also identified, including: UK Government (e.g. Department for Business, Energy and Industrial Strategy (BEIS) Heat Networks Team); Scottish Government (Hydrogen and Heat Networks Teams); and Scottish Futures Trust.

3.4 High-Level Technical Assessment

Based on the initial opportunity assessment and mapping exercise, a technical assessment was undertaken to shortlist a single preferred synergy opportunity to be taken forward into the economic assessment.

Section 6 (Technical Assessment) presents further information on the associated technical assessment methodology, including the associated screening criteria and scoring.

3.5 High-Level Economic Assessment

Based on the technical assessment, an initial, high-level economic assessment was undertaken to determine the associated viability of the shortlisted synergy opportunity.

Section 7 (Economic Assessment) presents details of the associated economic assessment methodology.

3.6 Online Workshops / Webinars

To supplement the assessments / findings, and to inform the overall Synergy Study, the methodology also included two online technical workshops, and a final overall webinar.

- Technical Workshop 1

  Technical Workshop 1 presented the data / information collected during the initial project and synergy opportunity identification, and also presented the proposed technical assessment screening criteria and scoring.

- Technical Workshop 2

  Technical Workshop 2 presented and confirmed the technical assessment screening, and also presented the proposed economic assessment methodology.

- Final Webinar

  The final webinar brought together UK Government Representatives and Case Study Presenters, and presented the findings of the Synergy Study.

Appendix B presents the workshop / webinar materials, including the associated presentations.

4 LITERATURE REVIEW

4.1 Overview

This Section summarises the literature review's main findings. Appendix A provides the Literature Review report.

4.2 Main Findings

- The review highlighted that hydrogen production is a well-established industrial process and the main research challenge is low or zero carbon hydrogen production at scale, and in an economically viable manner. It suggested that the retail price of hydrogen will be highly sensitive to the economies of scale, plant yield, location of the project and assumptions around inflation rate. The cost of green hydrogen produced from solar and wind power is likely to reduce in the future due to forecasted reduction in the cost of solar PV panels and offshore wind turbines. The review also touched on the challenges around storing and transporting hydrogen and indicated that improving energy efficiency of liquid hydrogen storage, and storage in organic compounds, such as ammonia, remain active areas of research.

- The concept of replacing natural gas by hydrogen for heating is currently being tested by household appliances manufacturers. The colourless and odourless nature of hydrogen flame presents substantial safety challenges which need to be addressed through further research and development.

- The impact of utilising heat as a by-product from hydrogen production largely depends on the hydrogen production process. It was noted that hydrogen production processes which use heat as a primary energy input in some cases have detrimental impact on the system efficiency if the heat required for hydrogen production is diverted elsewhere. Similarly, in certain type of electrolysers (such as PEM and solid oxide) reducing the operating temperature of electrolyser will lower the efficiency of the electrolysers.

- In the context of this study, where the focus is on recovering waste heat from hydrogen production, the review (including the various referenced literature sources) confirmed that recovering waste heat from electrolyser stacks should not have any negative impact on process efficiency. Indeed, the various literature sources suggested conversely that *the system efficiency of PEM electrolyser plants can increase by 14 to 32% by recovering waste heat*. The review indicated that the waste heat from PEM electrolysers can be recovered at 45 – 75°C and should be readily suited to use in heat networks. Further, one literature source[18] noted that value of waste heat from a PEM electrolyser is likely to be in the region of £27.3/MWh. This value is calculated by considering the average cost to consumers connected to heat networks and subtracting the capital and O&M elements of the cost.

- The literature review also touched on heat recovery from Steam Methane Reformation (SMR) processes. SMR is an endothermic process requiring heat in the process. Part of the SMR process releases heat which is typical recovered to re-use within the process. There is a potential to use waste heat from SMR in heat networks however so far the industry has focused on reusing the waste heat within the SMR process and making it more efficient.

[18] 'A Combined Heat and Green Hydrogen (CHH) Generator Integrated with a Heat Network' (D. Burrin, S. Roy, A.P. Roskilly, A. Smallbone). Energy Conservation and Management, 246 (2021), 114686.

5 SYNERGY OPPORTUNITY ASSESSMENT

5.1 Overview

This Section provides a summary of the location and scale of the hydrogen production and heat network projects and synergy opportunities identified by the study.

5.2 Hydrogen Production Projects by Cluster

Table 5-1 presents a summary of the identified hydrogen production projects in each of the three target clusters.

Table 5-1: HYDROGEN PRODUCTION PROJECTS

Project	*Stakeholders / Partners*	*Type*	*Size*	*Status*	*Description*
ABERDEEN					
Cove Fuelling Station	Hydrogenics / ACHES (Aberdeen City Council)	Green	130 kg/day	EXISTING Operational 2017	Re-fuelling station with two delivery pressures.
Kitty Brewster Fuelling Station	BOC / ACHES (Aberdeen City Council)	Green	360 kg/day	EXISTING Operational 2018	Re-fuelling station with two delivery pressures.
Dolphyn	ERM / NEL Doosan / ODE / Tratebel Engie / PPI	Green	P1: 2 MW P2: 10 MW P3: 100MW	PROPOSED P1 FEED P1: 2021 P2: 2026 P3: 2030	Floating offshore windfarm with green hydrogen production.
Hydrogen Hub	Aberdeen City Council	Green	500 kg/day (to 3500 kg/day)	PROPOSED Planning 2025 – 2030 (Financial Close 2022)	Through the Aberdeen Hydrogen Hub, there is a requirement to provide a programme of investments in renewable (green) hydrogen production to supply Aberdeen's bus and public sector fleets. The initial demand will be 500 kg/day with forecasted demand of 3.5 tonnes/day by 2030. The initial phase of the Aberdeen Hydrogen Hub is supported by the Scottish Government's Energy Transition Fund.
Acorn Project	Pale Blue Dot Energy / SSE/ Petrofac NECCUS / LNG9 / GB-Tron / Strathclyde University	Blue	200MW	PROPOSED Pre-FEED 2026	
LEEDS					
Leeds Bradford Airport	Leeds Bradford Airport / ITM Power	Green	Approx. 1000 kg/day	PROPOSED Feasibility 2026	Re-fuelling station.
Leeds Waste and Recycling Centre	Leeds City Council	Green	Approx. 1000 kg/day	PROPOSED Feasibility 2026	Re-fuelling station.

Project	*Stakeholders / Partners*	*Type*	*Size*	*Status*	*Description*
HUMBER REGION					
Gigastack	ITM Power / Ørsted / Phillips 66	Green	P1: 5 MW to P3: 100 MW	PROPOSED FEED 2021 –	Three phases, part of Humber Zero.
Altalto Immingham	British Airways / Velocys			PROPOSED Feasibility 2022	Project to produce Synthetic Aviation Fuels (SAF) and naphtha from waste.
Equinor	Equinor	Green		PROPOSED Concept / Feasibility 2025 - 2040	
Uniper (Blue)	Uniper / VPI / Phillips 66	Blue	700 MW	PROPOSED Pre-FEED 2025	
Uniper (Green)	Uniper / Toyota / Association of British Ports / Siemens	Green	20 – 100 MW	PROPOSED Pre-FEED 2025	
H2H Saltend	Equinor / Trion Power / Mitsubishi Power	Blue	P1: 600 MW	PROPOSED Pre-FEED 2027	Also includes the potential for 2 additional 600 MW phases, considering 100% hydrogen conversion.

NOTE: The 'H21 Project' is a grid injection and distribution project that has been looking at the use of hydrogen in the Leeds City gas network. While the hydrogen use is in the Leeds area, the associated hydrogen production to take place on a large scale in the Teesside area, approximately 65 miles north of Leeds. Therefore, with regards to the Leeds synergy, H21 Project hydrogen production is not considered. Notwithstanding, the 'East Coast Hydrogen Project' is an expansion of this project which looks at a phased introduction of hydrogen to the North East gas network, ultimately looking to expand to other clusters such as Hynet in the North West. Therefore, strategic location of hydrogen production projects within this network could present a future synergistic opportunities.

5.3 District Heating Network Projects by Cluster

The assessment of district heating projects included the following:

- Existing / planned district heating networks;
- Planned large-scale developments (potential new build heat networks);
- Existing large heat loads (potential retrofit heat networks); and,
- Low-density buildings within the / in close proximity to area of interest.

Firstly, the review considered existing or planned district heating networks.

For existing schemes, the overall heat loads should be known, and, for planned schemes, heat demand assessments should have been completed as part of previous feasibility studies required during their development.

The review then considered planned new large-scale developments, presumed to present good potential for new heat networks. The associated planning documents include important details (such as the number, size and thermal efficiency of buildings) which can then be analysed and compared with benchmarking data to estimate an approximate annual heat demand.

A similar process was carried out to assess heat demands associated with large existing buildings/sites that could act as anchor loads for new district heating networks. Where available, actual billing data for existing sites was analysed to estimate an approximate annual heat demand. Where such data wasn't available, benchmarking values were used in combination with building characteristics, such as age and floor area.

Finally, a similar assessment was carried out for low-density buildings (housing). Ramboll have developed in-house tools to analyse areas of housing by using assumptions, enabling the calculation of an approximate heat demand.

The combination of these stages provide an estimated overall peak and annual demand for existing, planned and potential new heat networks across the three clusters.

5.4 Aberdeen Cluster

5.4.1 District Heating Network Status

Aberdeen has several existing and proposed district heating networks.

Table 5-2 presents the Aberdeen district heating networks identified.

Table 5-2: ABERDEEN DISTRICT HEATING NETWORKS

Project Location	Project Name	Asset	Status
City Centre	Kincorth	District Heating Network	Existing
City Centre	Seaton	District Heating Network	Existing
North City Centre	Tillydrone	District Heating Network	Existing
City Centre	University of Aberdeen	District Heating Network	Existing
East Aberdeen	Hazlehead	District Heating Network	Existing
East Aberdeen	Stockethill	District Heating Network	Existing
City Centre	Torry	District Heating Network	Proposed

5.4.2 Hydrogen Waste Heat Assessment

Table 5-1 summarises the hydrogen production projects within this cluster.

Based on process knowledge and discussions with equipment / technology suppliers, Table 5-3 presents a summary of the waste heat potential associated with these projects.

Table 5-3: WASTE HEAT (FROM ABERDEEN HYDROGEN PRODUCTION) POTENTIAL

Project Name	Energy Input (MW)	Waste Heat Potential (MW)
Cove Fuelling Station	0.300	0.076
Kitty Brewster Fuelling Station	0.800	0.210
Dolphyn	P1: 2 MW to P3: 100MW	0.440 to 22
Hydrogen Hub	1.125 to 8	0.325 to 2.0
Acorn Project	200	6

For the two fuelling stations, the energy input is less than the waste heat potential. However, here is should be noted that, as the hydrogen is being used for transport, there is a requirement for compression. Therefore, in addition to the waste heat potential from hydrogen production, there should be additional waste heat potential from any associated compression cooling.

Of the hydrogen production projects listed:

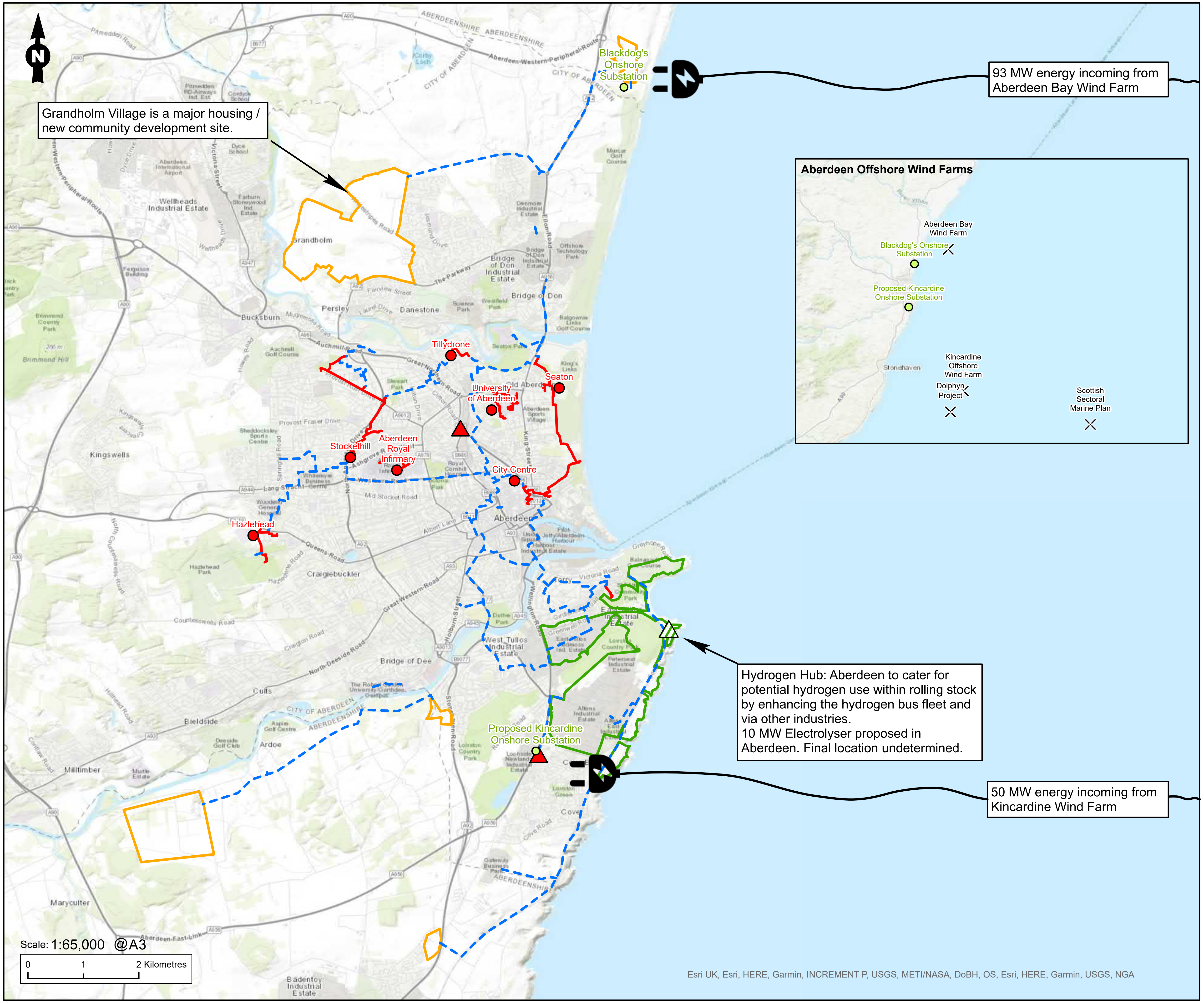
- Dolphyn is a floating offshore windfarm with hydrogen production. The associated electrolysers are being designed to be attached to a platform on the wind turbine foundation, and the hydrogen produced would be transported to shore by pipeline. Therefore, use of any waste heat could present a challenge due to the location of the hydrogen production process in relation to any potential Aberdeen heat demand / heat off takers.
- The Acorn project is located close to St Fergus, which is 35 miles north of Aberdeen. Therefore, use of any waste heat could present a challenge due to the location of the hydrogen production process in relation to any potential Aberdeen heat demand / heat off takers. The status / timescale of this project will ultimately depend on a positive outcome in the UK's carbon capture, usage and storage (CCUS) cluster sequencing.

5.4.3 Aberdeen – Mapping Potential Synergies

Based on the above, it is noted that Aberdeen has a number of existing district heat networks across the city, and aims to build a city-wide heat network.

Through the H_2 Aberdeen Programme, Aberdeen is also on the forefront of Hydrogen production and aims to create a hydrogen economy in the region. In addition, a number of offshore wind farms are already commissioned or currently under construction, and these will generate renewable electricity which could also be utilised for green hydrogen production.

The Figure overleaf presents the Aberdeen Synergy mapping. It should be noted that two of the hydrogen production projects identified (the Dolphyn and Acorn projects) are not shown due to them not being in close proximity to Aberdeen City Centre.



Legend

- Existing Heat Networks
- Potential Heat Networks
- Existing Heat Sources
- Existing Hydrogen Projects
- Potential Green Hydrogen Projects
- Energy Transition Zone
- Proposed Development Boundaries
- Wind Farm Onshore Substation
- Offshore Wind Farm
- Offshore Wind Incoming Power

Figure Title

Aberdeen - Synergy Identification

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5.5 Leeds Cluster

5.5.1 District Heating Network Status

Leeds has several existing and proposed district heating networks.

Table 5-4 provides summary details of district heating networks identified in Leeds.

Table 5-4: LEEDS DISTRICT HEATING NETWORKS

Project Location	Project Name	Asset	Status
City Centre / Aire Valley	Leeds City Centre and the Aire Valley: Phase 1	District Heating Network	Existing
City Centre / Aire Valley	Leeds City Centre and the Aire Valley: Phase 2	District Heating Network	Existing
City Centre / Aire Valley	Leeds City Centre and the Aire Valley: Phase 3	District Heating Network	Proposed

5.5.2 Hydrogen Waste Heat Assessment

Table 5-1 summarises the hydrogen production projects within this cluster.

Based on process knowledge and discussions with equipment / technology suppliers, Table 5-5 presents a summary of the waste heat (from Leeds hydrogen production) potential. It should be noted that both hydrogen production processes are still in the process of establishing a final hydrogen demand, and therefore the size (hydrogen production capacity) is still to be fixed.

Table 5-5: WASTE HEAT (FROM LEEDS HYDROGEN PRODUCTION) POTENTIAL

Project Name	Energy Input (MW)	Waste Heat Potential (MW)
Leeds Bradford Airport	2.2	0.582
Leeds Waste and Recycling Centre	2.2	0.582

For both these projects, the hydrogen would be produced for fuelling stations. However, there it should be noted that, as the hydrogen is being used for transport, there is a requirement for compression. Therefore, in addition to the waste heat potential from hydrogen production, there would be additional waste heat potential from any associated compression cooling.

Of the hydrogen production projects listed it was noted that:

- Leeds Bradford Airport has plans for an expansion with a new terminal building. In tandem with the hydrogen production plans, this presents a good opportunity to assess the heating demand / infrastructure of the new terminal building and ensure the best opportunity for waste heat recovery and use.
- The Leeds Waste and Recycling Centre plants hinge on a common dilemma of investment in hydrogen infrastructure and vehicle conversion. However, the refuse truck fleet is one of the larger fleets of vehicles under Leeds City Council's control, and therefore can be strategically converted in its entirety with planned investment. Further, the Waste and Recycling Centre already has a tie into the district heating network, and therefore waste heat recovery and use in the network is theoretically simplified (as much of the required infrastructure is likely to be in place).

5.5.3 Leeds – Mapping Potential Synergies

Based on the above, it is noted that Leeds has a large existing district heating network, with ambition to extend capacity up to 150 MW in the coming years.

However, Leeds has limited plans for hydrogen production, with only Leeds Bradford Airport and Leeds Waste and Recycling Centre projects under consideration.

The Figure overleaf presents the Leeds synergy mapping.

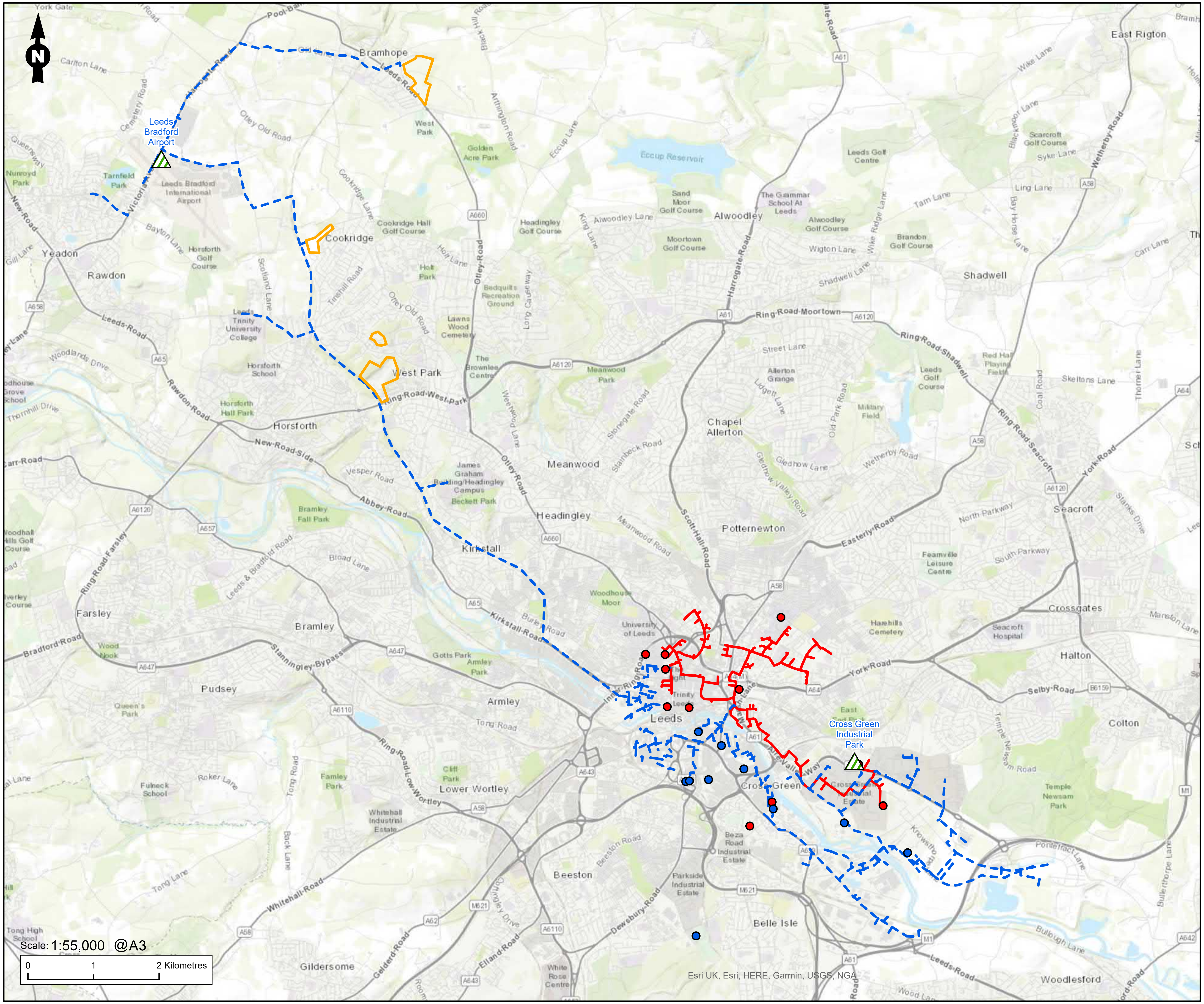

Figure Title

Leeds - Synergy Identification

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5.6 Humber Region

5.6.1 District Heating Network Status

The Humber region has no existing district heating networks, but does have a number of proposed district heating networks.

Table 5-6 presents the Humber region district heating networks identified.

Table 5-6: HUMBER REGION HEATING NETWORKS

Project Location	Project Name	Asset	Status
City Centre	Hull District Heating Network Phase 1	District Heating Network	Planning
City Centre	Hull District Heating Network Phase 2	District Heating Network	Planning
City Centre	Hull District Heating Network Phase 3	District Heating Network	Planning
North East Lincolnshire	Stallingborough Enterprise zone	District Heating Network	Masterplanning
North East Lincolnshire	Immingham Town	District Heating Network	Masterplanning
North East Lincolnshire	Cromwell Road	District Heating Network	Masterplanning
North East Lincolnshire	Stallingborough Enterprise zone	District Heating Network	Masterplanning
North East Lincolnshire	Stallingborough Enterprise zone	District Heating Network	Masterplanning

5.6.2 Hydrogen Waste Heat Assessment

Table 5-1 summarises the hydrogen production projects within this cluster.

Based on process knowledge and discussions with equipment / technology suppliers, Table 5-7 presents a summary of the waste heat (from Humber region hydrogen production) potential.

Table 5-7: WASTE HEAT (FROM HUMBER REGION HYDROGEN PRODUCTION) POTENTIAL

Project Name	Energy Input (MW)	Waste Heat Potential (MW)
Gigastack	P1: 5 MW to P3: 100MW	1.1 to 22
Altalto Immingham	Unknown	Unknown
Equinor	Not Specified / Unknown	Not Specified / Unknown
Uniper (Blue)	700	28
Uniper (Green)	20 to 100	4.4 to 22
H2H Saltend	P1: 600 (2 additional 600 MW Phases)	18.5 (up to 55.5)

Of the hydrogen production projects listed, it was noted that the Uniper (Blue Hydrogen) and H2H Saltend project status / timescales will depend on a positive outcome in the UK's carbon capture, usage and storage (CCUS) cluster sequencing.

5.6.3 Synergy Mapping

Based on the above, three separate sub-synergies were identified in the Humber region:

- Beverley;
- Hull; and,
- South Humber.

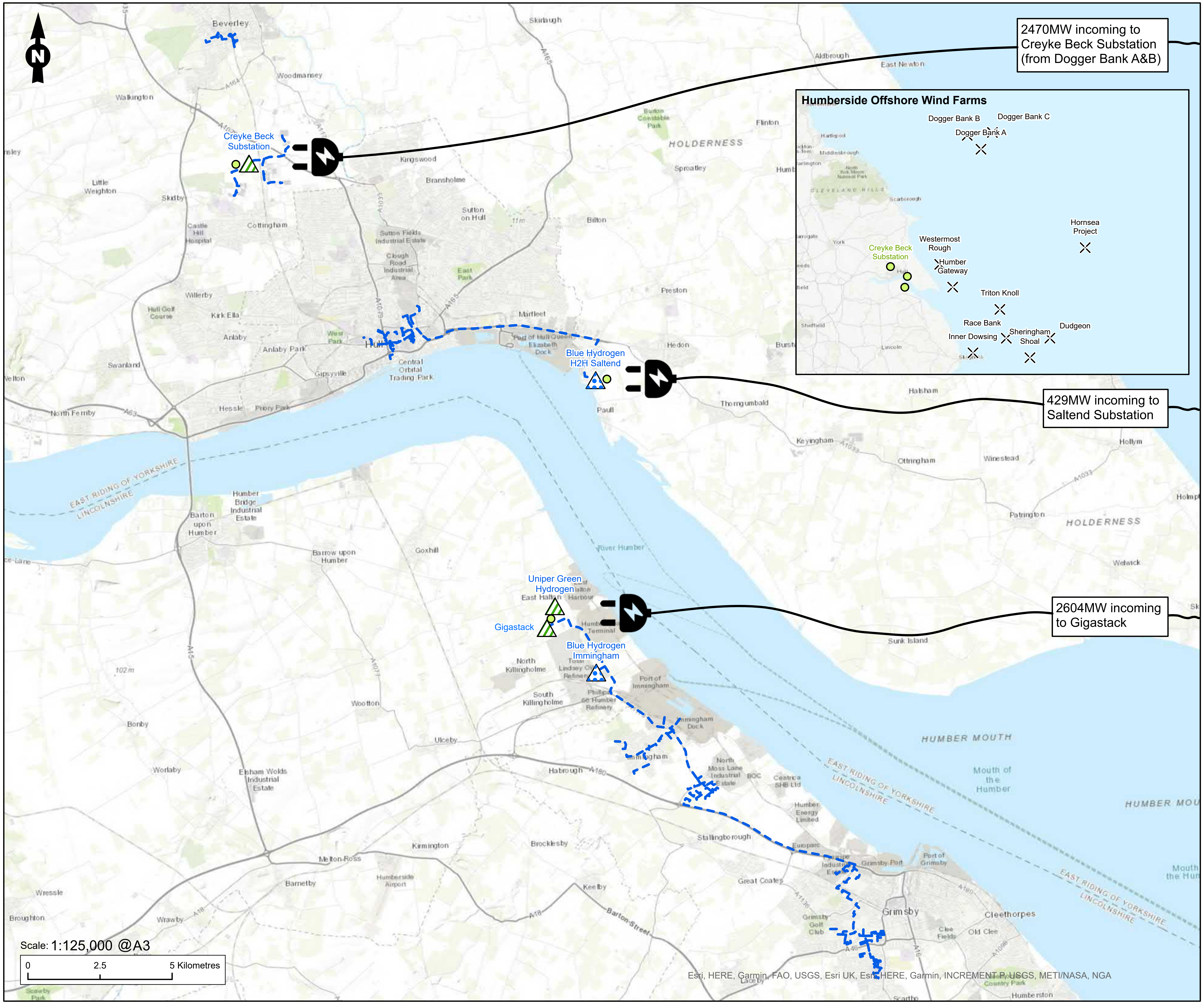
Beverley has a proposed heat network along with a number of greenhouses which could receive waste heat from the Equinor hydrogen production project.

Hull has a proposed town centre heat network which could receive waste heat from the H2H Saltend hydrogen production project.

The South Humber has five proposed heat networks which could receive waste heat from the Gigastack and Uniper hydrogen production projects.

In addition, a number of offshore wind farms are already commissioned or currently under construction, and these will generate renewable electricity which could also be utilised for green hydrogen production.

The Figure overleaf presents the Humber region synergy mapping.



Legend

- Potential Heat Networks
- Potential Blue Hydrogen Projects
- Potential Green Hydrogen Projects
- Wind Farm Onshore Substation
- Offshore Wind Farm
- Offshore Wind Incoming Power

Figure Title

Humber - Synergy Identification

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6 TECHNICAL ASSESSMENT

6.1 Overview

This Section provides a summary of the initial technical assessment of the various potential synergy opportunities identified across the three clusters.

6.2 Screening and Scoring Criteria

For any project, there are many factors (associated enablers and blockers) that can have an effect on its feasibility. However, within this Synergy Study, focus has been given to the specific factors which are likely to have an effect on the feasibility of a synergy project of waste heat recovery from hydrogen production.

Table 6-1 sets out the factors, enablers and blockers that were addressed by the assessment.

Table 6-1: TECHNICAL ASSESSMENT FACTORS, ENABLERS AND BLOCKERS

Factors	Enablers	Blockers
Technical	• Large waste heat (from hydrogen production) availability. • Good heat quality supply (e.g. high temperature). • Large growth potential (for hydrogen production). • Sufficient heat demand. • Proximity to heat networks. • Density of heat demand. • Low heat network temperature.	• Small waste heat (from hydrogen production) availability. • Low / poor heat quality supply (e.g. low temperature). • Small growth potential (for hydrogen production) • Incompatible heat demand. • Availability of cost-effective alternative heat sources. • High heat network temperature.
Commercial	• Incentives for hydrogen production operator. • Incentives to heat network operator. • High network fuel costs.	• High capital investment. • Low network fuel costs. • Lack of stakeholder coordination / interaction.
Policy	• Heat hierarchy implementation. • Proactive planning policies to support hydrogen and district heat network synergies.	• Undefined planning policies. • Government funding.

The following provides some further detail around the key implications of some of these factors:

- Technical: Waste Heat Availability

  If large quantities of waste heat are available then the revenue to the hydrogen project will be higher.

  Also higher quantity of waste heat supply will enable more flexibility over a project life cycle and reduce the reliance on backup solutions, such as electric boilers.

- Technical: Heat Quality

  Heat quality is related to the temperature of the waste heat.

  Regarding new heating technologies, low grade (low quality) waste heat is not useless, as heat pump configurations can be used to boost lower temperature streams to the required heat network temperatures.

  However, there is a CAPEX and OPEX cost associated with doing this which needs to be considered in the overall plans for a synergy.

- Technical: Proximity and Network Routing

  The proximity of the hydrogen production project to the district heating network is of key importance. One of the largest costs of a district heating network / system is the pipework which carries the water to and from the users and to and from the heating interface. Therefore, it is not just proximity but understanding the routing of the pipes also. If the pipes must cross over large civil structures, such as roads and railways, this can add a lot of cost to the district heating network / system.

- Density of Heat Demand

  Low density of heat demand means lower amount of heat delivered per meter length of the heat network, also low heat demand can result in underutilisation of waste heat available from hydrogen. Both these factors can negatively affect the returns on investment.

Table 6-2 sets out the screening criteria and associated scoring weighting applied through the assessment.

Table 6-2: TECHNICAL ASSESSMENT SCREENING CRITERIA, AND ASSOCIATED SCORING WEIGHTING

Criteria	Weighting	Comments / Notes
Waste Heat Availability (Max)	20%	Intermittency and quantity of waste heat
Heat Demand (Max)	20%	Existing and planned district heat networks
Proximity / Distance	20%	Proximity of hydrogen production to district heat network
Heat Quality (Temp)	10%	Grade of waste heat
Hydrogen Production Growth Potential	5%	Secured future waste heat
District Heating Network Growth Potential	5%	Secured future heat load
Level of Stakeholder Interest	10%	Engagement of local / private stakeholders and planning authorities
Timescale to Implementation	5%	At concept / FEED / planning / development
Transferability	5%	Transferability of study outcomes between locations

6.3 Technical Assessment Results

A total of five key synergies were identified across the three clusters:

- Aberdeen City Centre;
- Leeds City Centre;
- Humber Region: Beverley;
- Humber Region: Hull; and,
- Humber Region: South Humber.

Using the available and collated project characterisation data / information, and the weightings described above, each synergy was scored 0 – 5[19]. The score was totalled to give an overall score.

The initial results were discussed with stakeholders in Technical Workshop 1, and revised taking into account stakeholder feedback before shortlisting the preferred synergy for economic assessment.

Table 6-3 summarises the technical assessment results.

Table 6-3: TECHNICAL ASSESSMENT RESULTS

	Aberdeen City Centre	Leeds City Centre	Beverley	Hull	South Humber
Waste Heat Availability (Max)	3	1	4	5	5

[19] A score of '0' was given for the least favourable conditions, and a score of '5' was given for more advantageous conditions.

Heat Demand (Max)	5	5	3	4	4
Proximity / Distance	4	4	3	3	4
Heat Quality (Temp)	2	2	2	2	2
Hydrogen Production Growth Potential	5	2	4	5	5
DHN Growth Potential	5	5	2	4	4
Level of Stakeholder Interest	4	2	2	4	4
Timescale to Implementation	5	1	2	4	4
Transferability	4	4	4	3	5
Scoring	3.95	3.00	3.00	3.80	4.10

6.4 Shortlisting the Preferred Synergy

Based on the findings presented in Table 6-3, South Humber was selected as the preferred synergy to be taken forward for the economic modelling and assessment.

This synergy presents three hydrogen projects planned in close proximity; two very substantial (2 x 100MW) green hydrogen projects, one of which (Gigastack)) is currently at FEED stage, and another large (700 MW) blue hydrogen project. In addition, within the South Humber region, there are also several potential heat networks which have been subject to previous feasibility studies, and identified as potentially viable. The previous feasibility studies also noted that the provision of information on the potential availability of additional heat sources (such as waste heat from hydrogen production) could support the growth and progression of these district heating projects.

In addition, an important consideration for this study is the sharing and transferability of information and experience to other projects. In particular, the transferability of the economic modelling could present insight into the costs and the principles of heat recovery from different forms of hydrogen production. Both green and blue hydrogen processes have waste heat available and both processes play an important role in the hydrogen economy, and the South Humber region includes both of these processes.

7 ECONOMIC ASSESSMENT

7.1 Overview

Following technical assessment and shortlisting of the most attractive synergy opportunity, an economic model was developed to provide an initial high-level assessment of the project's potential economic viability. This section summarises the findings of this exercise.

Modelling assumptions and results are presented, followed by a sensitivity analysis to assist in the development of guidelines for other possible synergies.

It should be stressed here that this is an initial and very-high-level assessment and the results should be considered as indicative only, intended primarily to steer decision-making as to whether to progress investigation of the opportunity further.

7.2 Assumptions

7.2.1 Scenarios Modelled

The green hydrogen projects in South Humber region (Gigastack and Uniper (green)) were considered. The hydrogen production capacity in the initial phase of these projects is expected to be 20 MW with maximum waste heat available approximately 4.4 MW.

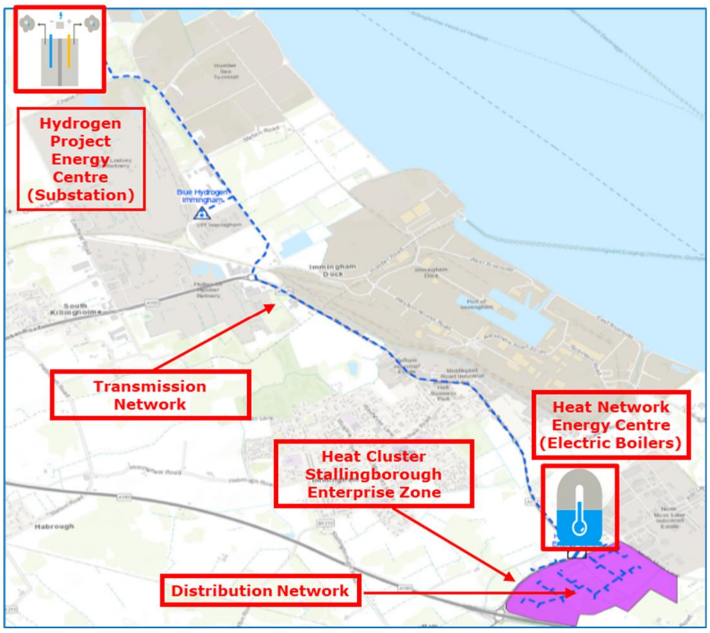
Stallingborough Enterprise Zone (SEZ), which is one of the heat demand clusters identified by North East Lincolnshire Council for implementation of heat networks, was considered as the heat load. The heat demand at SEZ is from anticipated new and commercial developments. The distance between the green hydrogen projects and SEZ is approximately 10 km.

It was assumed that the hydrogen production project energy centre will consist of a substation located at hydrogen production project site, and will consist of a substation recovering heat from the hydrogen production plant before discharging it into the heat transmission network.

The heat network energy centre will be located at the other end of heat transmission network, and will consist of electric boilers providing top up and back up heating capacity. Heat network energy centre will discharge heat in the distribution network connected to individual heat loads.

Figure 7-1 presents the synergy project modelling elements, covering the placement of the energy centres, and associated transmission and distribution networks.

Figure 7-1: SYNERGY PROJECT SCENARIO MODELLING ELEMENTS



For the synergy project, the heat demand modelling assumptions comprised:

- Hydrogen Production Capacity
  - Green Hydrogen (Gigastack or Uniper Green)
  - 20 MW
- Waste Heat Available
  - Peak: 4.4 MW
  - Average: 2.64 MW (60% Capacity factor)
- Heat Demand[20]
  - Peak: 15 MW
  - Annual: 24.6 GWh
- Key Energy supply equipment
  - Primary Energy source: Hydrogen waste heat (4.4 MW peak capacity)
  - Secondary Energy Source: Electric boilers (15 MW peak capacity. Used for back up and to meet peak heat loads)
  - Energy storage: Thermal store (100 m^3 thermal store located in the Heat Network Energy Centre)
- Heat Supply[21]
  - Hydrogen Waste Heat: 75%
  - Electric Boilers: 25%
- Operating Temperature
  - Waste Heat supply[22]: 80 / 50°C
  - Heat Network: 70 / 40°C

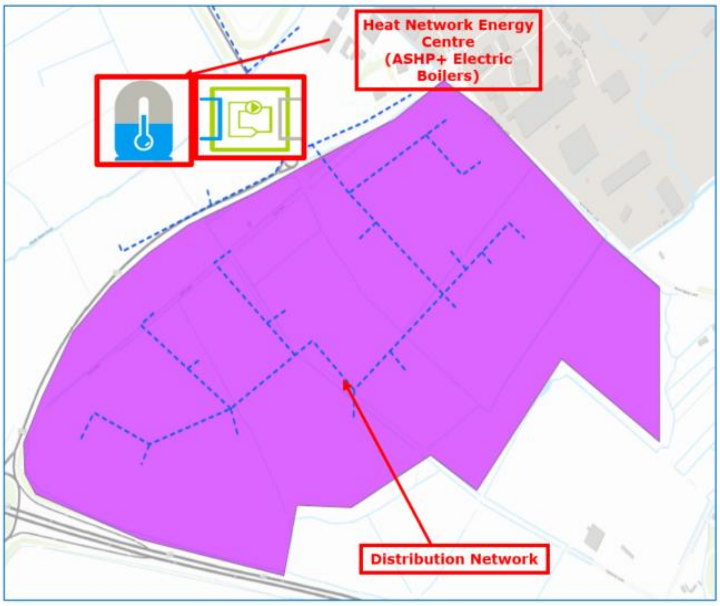
The synergy project scenario was then compared against a counterfactual scenario based on heat network supplied by alternative low / zero carbon heat source.

For the purpose of the modelling, Air Source Heat Pumps (ASHP) were considered as a primary heat source for the counterfactual scenario. Since there is no heat recovery from hydrogen production, the transmission network is not required. A single energy centre local to the heat demand cluster with distribution network was considered.

Figure 7-2 presents the counterfactual scenario modelling assumptions.

[20] From North Lincolnshire Heat Mapping and Master Planning Report.
[21] From Energy Modelling
[22] From Electrolyser Suppliers for Green Hydrogen Projects in South Humber Region.

Figure 7-2: COUNTERFACTUAL PROJECT SCENARIO MODELLING ELEMENTS



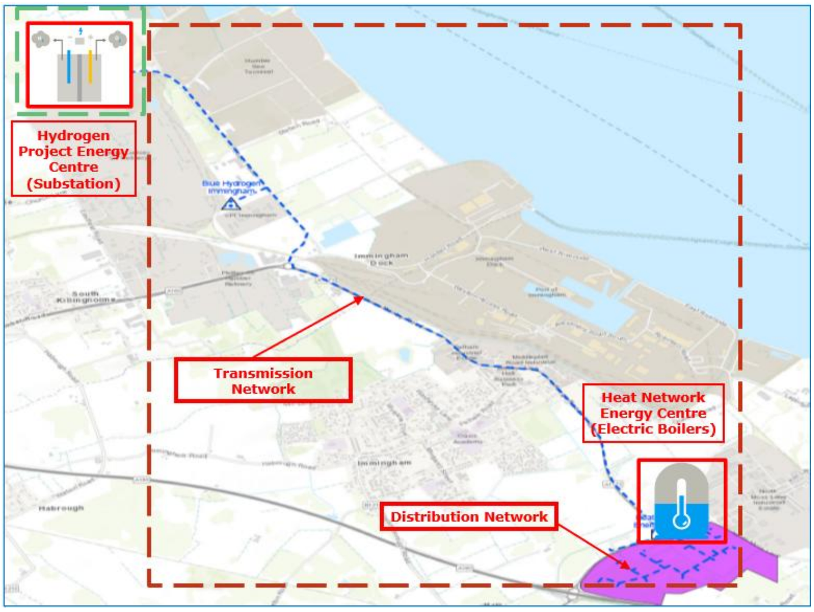
All other considerations around heat demand, energy storage, operating temperatures were assumed to be the same as the synergy project scenario.

7.2.2 Allocation of Project Costs

In the synergy project scenario, it was assumed there are two stakeholders; the hydrogen project owner / operator and the DHN operator/owner.

Figure 7-3 presents the assumed division of project scope between the two stakeholders.

Figure 7-3: HYDROGEN (GREEN) AND DH (RED) BOUNDARIES FOR COST



It was assumed that the cost for the waste heat recovery substation and its associated energy centre investment and running costs are in the scope of hydrogen project. The transmission network, DHN energy centre and the distribution heat network was considered to be in the scope of the DHN project.

It was assumed heat sales take place in two stages; in the first stage the hydrogen project will sell the waste heat to DHN operator, and in the second stage the DHN operator will sell heat to the DHN consumers.

7.2.3 Other Assumptions

Table 7-1 provides details of other key assumptions used in the model.

Table 7-1: ASSUMPTION MODEL

Parameter	Unit	Value
Project Life Cycle	Year	40
Discount Rate	%	3.5

With regards to carbon emissions, it was assumed that all hydrogen in this scenario can be classified as Zero Carbon. All the emissions arising from the project are therefore driven by power imported from the National Grid. Data on carbon intensity of the power grid over the project lifetime was taken from the UK Government Green Book Tables.

7.3 Cost Assumptions

Table 7-2 provides the key cost assumptions used in the modelling process.

Table 7-2: SUMMARY OF KEY COST ASSUMPTIONS

Item	Assumptions
CAPEX	Based on Ramboll's internal supplier database and quotes received. Table 7-3 provides a detailed cost breakdown.
REPEX	Waste Heat from H2 HEX Connection: 50% of Capex after 25 years Electric boilers: 80% of CAPEX after 20 years Heat Pump: 50% of Capex after 15 years Pumping equipment: 100% of CAPEX after 20 years Water Treatment and Pressurisation: 100% of CAPEX after 20 years Substations: 100% after 20 years DH pipework: 100% after 60 years
O&M	Based on a database of supplier data gathered by Ramboll in several previous DH projects.
Phasing	The project start year is assumed to be 2025, in line with the commissioning of the H2 facility and the heat is assumed to be delivered to the site in 2026.
Heat Sale Rate	Levelised cost of energy +10%

Table 7-3 provides a detailed technology cost assumption breakdown.

Table 7-3: TECHNOLOGY COSTS BREAKDOWN

CAPEX ITEM	Unit	Value	Source	Scenario
Waste Heat Recovery HEX	k£	73.5	Supplier's Quote	H2
Electric Boilers	k£	720.8	Supplier's Quote	All
ASHPs	k£	1,800.0	Supplier's Quote	Counterfactual

7.4 Revenue Streams

7.4.1 Hydrogen Production

The addition of a waste heat recovery plant in the hydrogen facility can bring additional streams of revenue and savings for the plant. The identified ones are:

- Revenues from Waste Heat sales to DHN; and,

- Electricity Savings in cooling tower, 2% of electricity consumption was assumed.

Given the novelty of this study in the UK, there are no previous benchmarks for waste heat recovery costs. Thus, a LCOE approach to determine the waste heat price has been adopted: the LCOE is given by the discounted capital, operational and replacement costs over the discounted waste energy produced for the lifetime of the project, in this case 40 years. The outcome is a price per MWh which guarantees no economic losses for the H_2 facility and represent the actual cost associated with running and maintaining the waste heat equipment. On top of the LCOE, a 10% is added to showcase a profit for the H_2 operator. It should be noted that the cost for the electrolyser and the other equipment associated with the hydrogen production are not part of this assessment and thus out of the cost boundaries.

7.4.2 District Heating Heat Sales

The same methodology as hydrogen facility heat sale was adopted to assess the heat selling price by the DHN operator to the customers of the SEZ. The DHN LCOE included the transmission and distribution networks, DHN energy centre technologies and building and energy costs, which include the waste heat and electricity. A 10% profit allowance was considered for calculating the heat sale rate. The same heat sale rate as calculated for the Synergy project scenario was used in the counterfactual scenario, in order to compare which the financial results.

Table 7-4 provides a summary table showing the assumed heat sale prices.

Table 7-4: HEAT SALE PRICES

Heat Sale	Unit	Value
Waste Heat from Hydrogen (From H2 Project to DHN)	£/MWh	2.8
DHN (From DHN to Consumers)	£/MWh	83.7

7.5 Financial Assessment Results

7.5.1 Costs & Revenues

Table 7-5 summarises the modelled costs and revenues from the different scenarios, and Figure 7-4 presents a comparison of the costs and revenues.

Table 7-5: SUMMARY OF COSTS AND REVENUES FROM MODELLED SCENARIOS

Item (Over 40 Years)	Unit	Synergy Project		Counterfactual Project
		H_2	DHN / Heat Network	
CAPEX	k£	146	17,259	11,221
OPEX	k£	200	8,202	6,117
REPEX	k£	35	632	2,411
Energy Costs	k£	1,362	33,878	62,271
Total Costs	k£	1,744	59,970	82,021
Heat Sales Revenue	k£	2,392	82,361	82,361

Figure 7-4: COMPARISION OF COSTS AND REVENUES

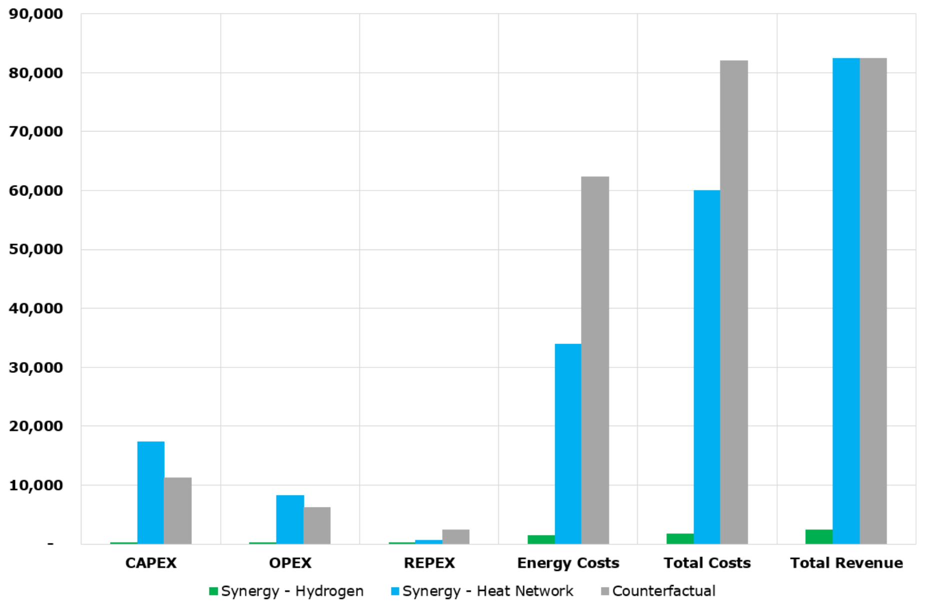
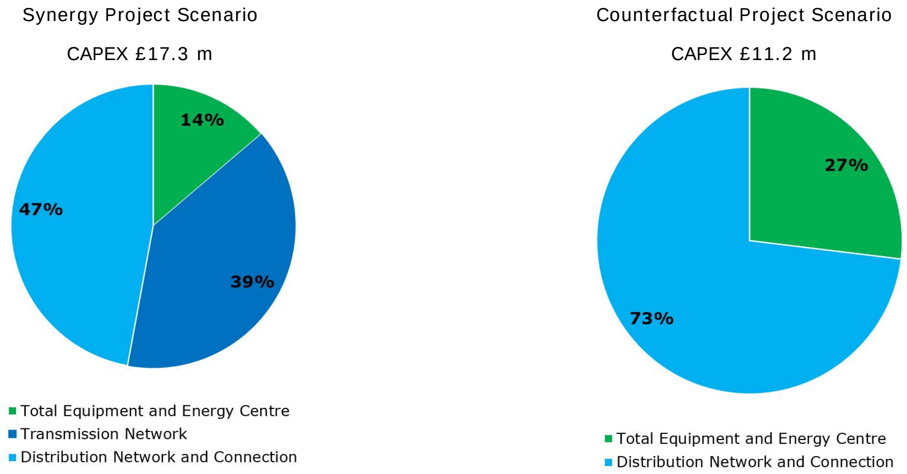


Table 7-6 summarises the CAPEX breakdown from the different modelled scenarios, and Figure 7-5 presents a comparison of the CAPEX.

Table 7-6: SUMMARY OF CAPEX FOR MODELLED SCENARIOS

CAPEX Item	Unit	H_2 Project	Synergy Project	Counterfactual Project
Energy Centre Equipment	k£	146	2,248	3,021
Transmission Network and Distribution Network and Building Connection	k£	-	15,011	8,200
Total	k£	146	17,259	11,221

Figure 7-5: COMPARISION OF SYNERGY WITH COUNTERFACTUAL SCENARIO



7.5.2 Discounted Cashflow Analysis

Key financial modelling results derived for the two scenarios are shown in Table 7-7 below, comprising ranges of internal rate of return (IRR) and net present value (NPV) calculated over the project life-cycle of 40 years.

Table 7-7: FINANCIAL MODELLING RESULTS

Item (Over 40 Years)	Unit	Synergy Project		Counterfactual Project
		H_2	DHN / Heat Network	
IRR	%	14.0	4.9	0.2
Final NPV	k£	284	4,072	(4,849)
Discounted Payback	Years	9	28	N / A
LCOE	£/MWh	2.5	76	93

The project cashflows for the different scenarios are presented respectively in Figure 7-6 for H2 project (Synergy Scenario), Figure 7-7 for the DHN operator (Synergy Scenario) and in Figure 7-8 for the DHN operator (Counterfactual Scenario).

Figure 7-6: H2 PROJECT (SYNERGY SCENARIO) CASHFLOW

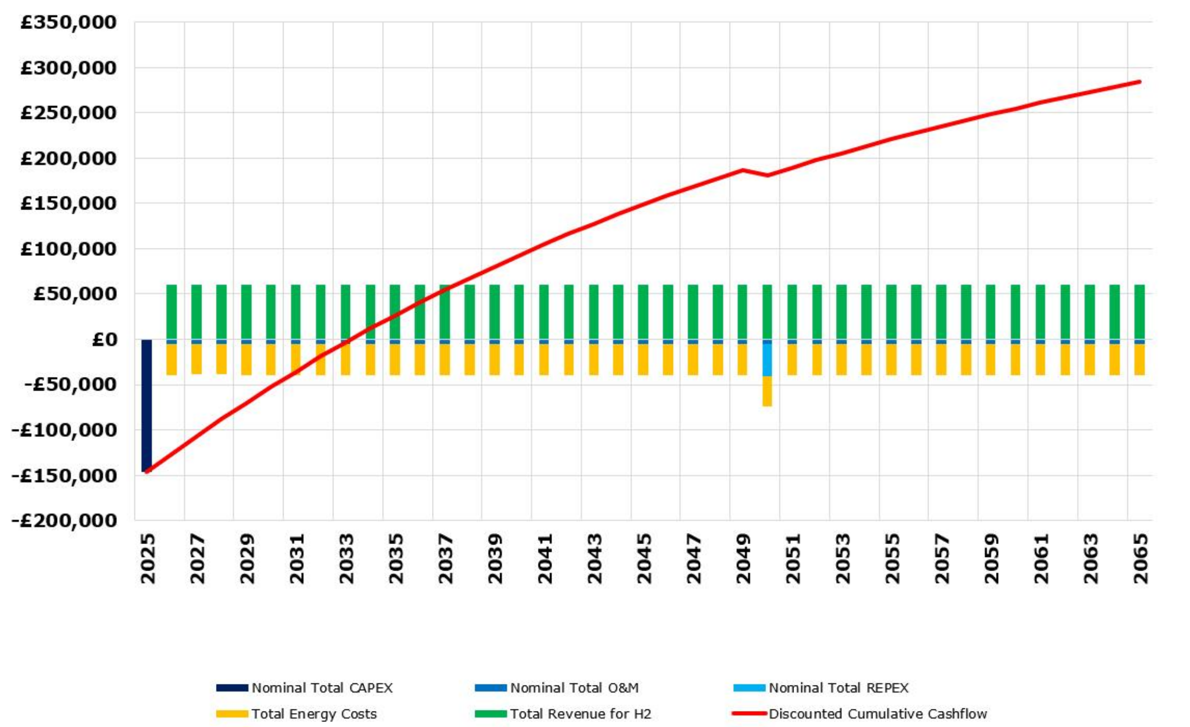


Figure 7-7: DHN OPERATOR (SYNERGY SCENARIO) CASHFLOW

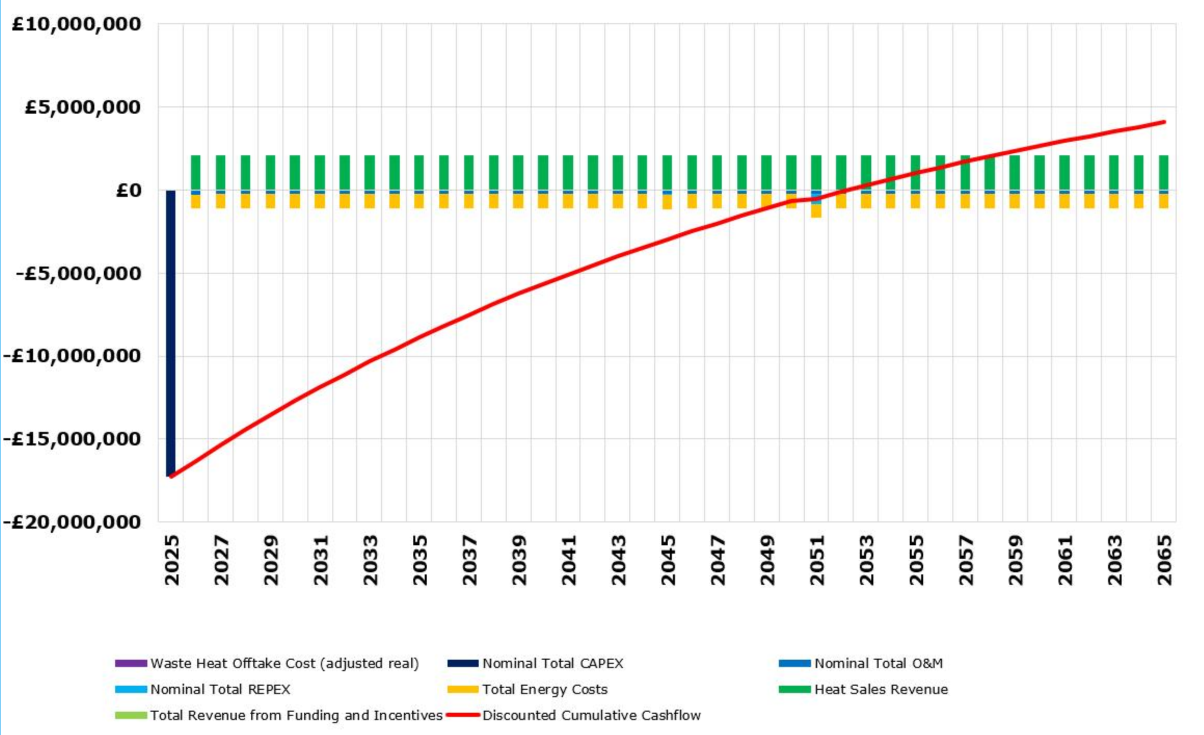
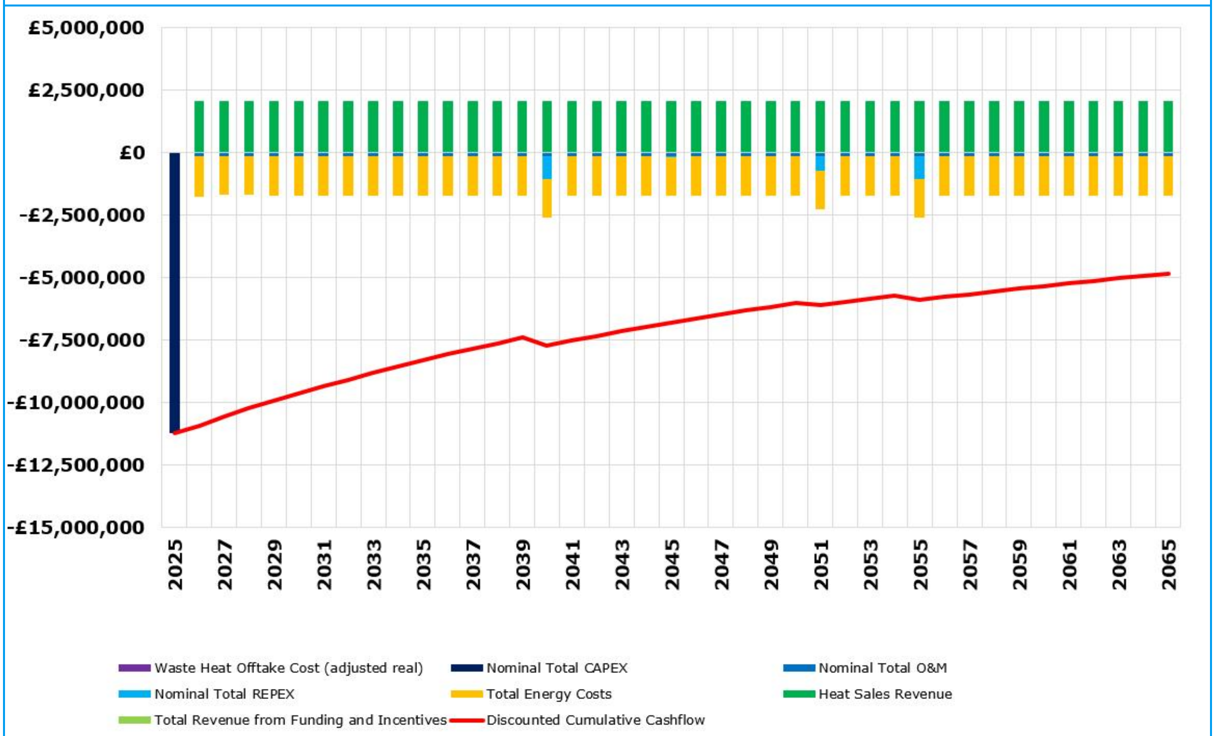


Figure 7-8: DHN OPERATOR (COUNTERFACTUAL SCENARIO) CASHFLOW



It can be seen from the results above that the Synergy project presents:

- For the hydrogen project, a very strong business case with positive NPV and 14% IRR;l

- For DHN / heat network projects, a more attractive business case compared to the counterfactual scenario.

7.5.3 Levelised Cost of Heat

As previously noted, the heat selling prices have been based on a LCOE analysis.

Thus, Table 7-8 presents the obtained LCOE for the different scenarios. The variable costs of the LCOE are given by energy costs, standing costs account for OPEX and REPEX, and the connection component for CAPEX costs.

Table 7-8: LCOE DIVISION AND COMPARISON

LCOE	Unit	Synergy Project		Counterfactual Project
		H_2 Project to DHN	DHN to Consumers	DHN to Consumers
Overall	£/MWh	2.5	76.0	92.9
Variable Component	£/MWh	1.84	34.4	63.3
Standing Component	£/MWh	0.3	8.8	8.3
Connection Component	£/MWh	0.4	32.7	21.3

7.5.4 Impact of Grant Funding

An assessment of different level of capital funding for the Synergy scenario has been carried out. Table 7-9 presents the resulting IRR. The IRR increase is compared against the DHN option with Synergy.

Table 7-9: IMPACT ON IRR (DHN) OF GRANT FUNDING

Grant Funding	IRR (40 years)	Variation from DHN H2 case
15% of CAPEX	6.2%	+1.3%
30% of CAPEX	7.8%	+2.9%
50% of CAPEX	11.5%	+6.6%

7.5.5 Sensitivity Analysis

A sensitivity analysis was carried out in line with the requirements of the scope and focused on the stakeholders of the Synergy project, the H_2 Facility and DHN Operator.

The modelled impact of each of the various sensitivity variables on project IRR for the DH Operator are shown in Table 7-10 and Figure 7-9.

In the Synergy project scenario, the waste heat temperature is higher than the DHN operating temperature and hence a substation is sufficient to off take the waste heat from the H2 projects.

However, if the waste heat temperature is lower than the heat network operating temperature then additional equipment such as boiler or heat pump will be required to increase the temperature of waste heat. This will have a negative impact on capital and operating cost of the project.

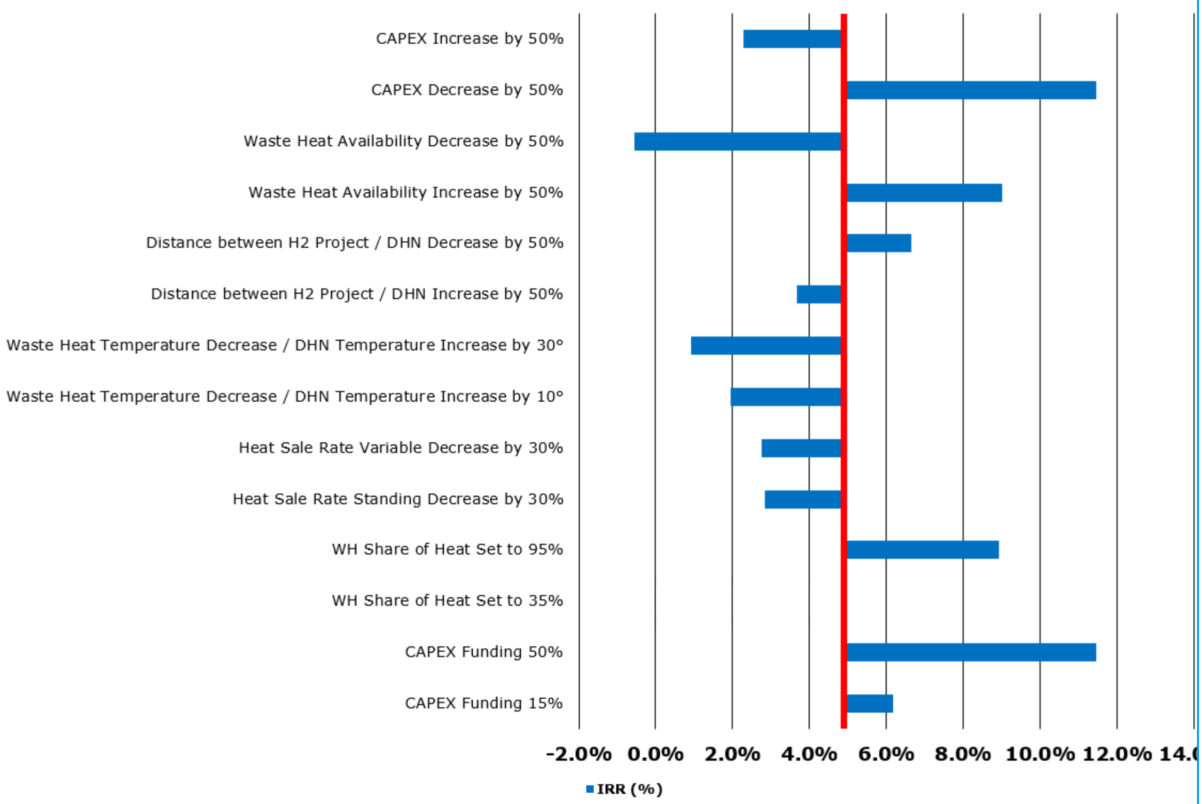
The impact of lower temperature of waste heat on the project performance was assessed by considering the waste heat temperature 10°C and 30°C lower than the DHN operating temperature.

Table 7-10: SENSITIVITY RESULTS DHN OPERATOR

Effect on IRR	Effect on IRR (%)	IRR (%)
CAPEX Increase by 50%	46%	2.3%
CAPEX Decrease by 50%	232%	11.5%
Waste Heat Availability Decrease by 50%	-11%	-0.5%

Waste Heat Availability Increase by 50%	183%	9.0%
Distance between H_2 Project / DHN Decrease by 50%	135%	6.7%
Distance between H_2 Project / DHN Increase by 50%	75%	3.7%
Waste Heat Temperature Decrease / DHN Temperature Increase by 30°	18%	0.9%
Waste Heat Temperature Decrease / DHN Temperature Increase by 10°	39%	1.9%
Heat Sale Rate Variable Decrease by 30%	56%	2.8%
Heat Sale Rate Standing Decrease by 30%	57%	2.8%
WH Share of Heat Set to 95%	181%	8.9%
WH Share of Heat Set to 35%	No IRR Available	No IRR Available

Figure 7-9: IRR VARIATION IN SENSITIVITY ANALYSIS, DH OPERATOR



The following observations are drawn from the analysis:

- For DHN operator the project is highly sensitive to the availability of waste heat / heat demand and the capital cost;
- Reducing the temperature of waste heat was also seen to make a significant impact on the project performance. IRR is expected to drop to 0.9% when waste heat temperature is 30°C lower than the heat network operating temperature which is likely to be the case for the blue hydrogen projects. It should be noted that this IRR is still better when compared with the counter factual scenario.

7.6 Environmental Assessment Results

7.6.1 Carbon Emissions

The total emissions and expected savings for the Synergy Project against the counterfactual case are presented below in Table 7-11.

Table 7-11: TOTAL EMISSION FROM THE DIFFERENT SCENARIOS AND CO2 SAVINGS FROM COUNTERFACTUAL; AFTER 40 YEARS

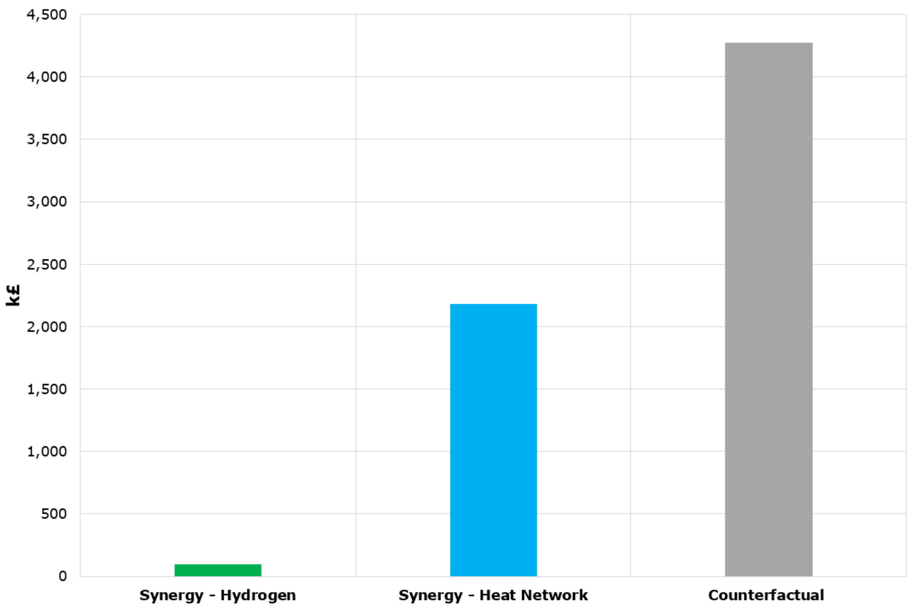
Item (Over 40 Years)	Unit	Synergy Project	Counterfactual Project
CO_2 Emissions	tonnes of CO_2	15,390	28,985
CO_2 Savings	tonnes of CO_2	13,590	-
Percentage CO_2 Reduction	%	47%	-

It should be noted that the carbon savings reported above are when compared with counterfactual scenario based on low / zero carbon heat source.

7.6.2 Air Quality

The results for air quality benefit costs are presented in Figure 7-10. The Synergy scenario provides over £2 million savings in air quality costs compared to the ASHP scenario.

Figure 7-10: AIR QUALITY BENEFIT COSTS



8 KEY FINDINGS, CONCLUSIONS & RECOMMENDATIONS

8.1 Key Findings

This Section summarises the key findings from the economic assessment.

8.1.1 Impact of Waste Heat Recovery on Hydrogen Production Projects

The technical impacts comprise:

- Improved System Efficiency:
  Utilising waste heat from hydrogen production will improve the system efficiency by 13 to 20%.
- Reduced Auxiliary Power Consumption:
  Since the excess heat generated from hydrogen production is recovered in heat networks the cooling load on the plant's cooling system can be reduced / eliminated resulting in lower auxiliary power consumption.
- Minimal Modification Requirements to the Plant:
  The waste heat from the hydrogen production plant can be recovered with minimal modifications to the hydrogen plant. The key consideration in making the project feasible is to specify the electrolyser to generate waste heat at the temperature suitable for DHN.
- Additional Space Requirements:
  Additional space will be required for heat offtake equipment. The space required will largely depend on the temperature of waste heat and scope split up between the hydrogen project and DHN.

The commercial impacts comprise:

- Additional Revenue Stream and Savings:
  The project will generation additional revenue stream through waste heat sale and savings through reduction in power consumption of cooling system.
- Enhanced Business Case:
  The waste heat recovery project is expected to have IRR>10% and positive NPV and hence presents an enhanced business case for hydrogen projects.
- Improved Revenue from Hydrogen Sale:
  The power saved in cooling systems can be utilised to generate additional hydrogen and hence the project has a potential to increase revenue from the hydrogen sale.

The environmental impacts comprise:

- Reduced Carbon Emissions:
  The project will reduce the auxiliary power consumption in cooling systems and hence will have a positive impact on carbon emissions.

8.1.2 Impact of Waste Heat Recovery on DHN Projects

The technical impacts comprise:

- Improved Efficiency of Heat Supply Equipment:
  In some cases where the waste heat temperature is lower than the heat network temperature additional equipment such as heat pump will be required to increase the temperature of waste heat, however the waste heat temperature from hydrogen production plants is expected in the region of 40 to 80°C which is still significantly higher than the temperature of heat streams available from other sources (e.g. river, sewer, ground etc) and hence the technologies such as heat pumps will have a better efficiency when compared with other heat streams..
- Reduced Energy Consumption:
  Waste heat available from hydrogen projects will reduce and/or eliminate the energy consumption from other heat supply equipment such as heat pumps and boilers.
- Additional Network Infrastructure Requirements:
  Heat network will need to be connected to the hydrogen projects. The additional length of

network will largely depend on the distance of hydrogen projects from the heat demand clusters.

- Additional Thermal Storage and Controls Requirements:
  The waste heat produced from hydrogen plants will be generated only when hydrogen is being produced. For most green hydrogen projects this will be the function of availability of renewable electricity. In order to maximise the utilisation of waste heat additional thermal storage capacity and considerations in designing of control systems are required.

The commercial impacts comprise:

- Additional Capital Costs:
  The initial capital cost is likely to be higher for the heat networks. The additional capital cost will largely depend on the distance between hydrogen projects and heat clusters, and the temperature of waste heat.
- Lower Operating Costs:
  Annual operating cost for heat networks is expected to be significantly lower compared to the other low / zero carbon technologies due to reduced expenditure on fuel / electricity.
- Enhanced Business Case:
  The analysis has shown that utilising the waste heat from hydrogen production is a more attractive option for heat networks than other low / zero carbon heat sources such as heat pumps.
- Reduced Cost to the Consumers:
  The assessment has shown that the cost to the consumers can be reduced by approximately 20% by utilising the waste heat from the hydrogen production.

The environmental impacts comprise:

- Carbon Savings:
  Utilising waste heat from hydrogen production is expected to have substantial carbon savings when compared with other low / zero carbon technologies. The assessment has shown that the carbon emissions over 40 year project lifecycle will be >45% lower when compared with heat Air Source Heat pumps.
- Air Quality Cost Benefits:
  Utilisation of waste heat will reduce / eliminate the fuel / electricity consumption resulting from heat supply equipment which will have a significant positive impact on the air quality. The total air quality cost benefits over project lifecycle are expected to be over £2m when compared with the alternative low / zero carbon technologies.

8.1.3 Critical (Economic) Success Factors

The sensitivity assessment was performed to identify the impact of various parameters on the project performance, and this suggested the success of the project is highly dependent on the following factors:

- High Heat Demand and Availability of Waste Heat:
  The project is highly sensitive to the availability of waste heat and heat demand. Therefore, the sufficient availability of waste heat and heat load is critical to make the project feasible.
- Capital Cost:
  The project is also very sensitive to the initial capital cost. Consequently, following enablers are identified to minimise the initial capital investment:
  - Waste heat temperature higher than the network operating temperature;
  - Lower network operating temperatures (e.g. for new developments and more efficient heating systems);
  - Close proximity of hydrogen projects from heat clusters; and,
  - Availability of grant funding.
- Heat Sale Rate:
  Heat sale rate will also have a significant impact on the project performance. In most

cases, the heat sale rate will depend on the availability of other low-cost heat alternatives and hence the early assessment of other alternatives and the strategic placement of the project is crucial.

8.1.4 Transferability

8.1.4.1 Transferability to Blue Hydrogen Projects

The economic assessment was performed for a green hydrogen project. However, the synergy concept is also applicable for the blue hydrogen projects.

The initial capital cost and operating cost is likely to be higher for waste heat recovery from blue hydrogen projects due to the lower temperature of waste heat. The initial assessment has indicated that the project IRR will reduce by approximately 18% for blue hydrogen project. However, the grade of waste heat available from the blue hydrogen projects is still better compared to the lowest / zero carbon heat sources. The assessment has also indicated that the project's financial performance is likely to be better than the counterfactual scenario based on alternative low / zero carbon technologies.

8.1.4.2 Transferability to UK Wide Projects

A high-level exercise was performed to assess the UK wide impact of the Synergy concept. In 2050, green hydrogen production in the UK is expected to be up to approximately 250 TWh[23]. Considering this figure and making same assumptions as indicated in this study, the following potential benefits to the UK wide energy system were identified:

- Annual Electricity Savings: 13.9 TWh
- Annual CO_2 Savings: 3.05 m tonnes
- Displacement of Hydrogen: If all waste heat from green hydrogen production is used to displace the direct use of hydrogen for heating then the demand on the green hydrogen demand can be reduced by approximately 33%. This will free up >80 TWh of renewable electricity which can be used for other applications.

8.2 Conclusions

A main conclusion from the economic assessment is that it is technically feasible to recover waste heat from hydrogen production without negatively impacting the production, and that it is economically attractive to utilise this waste heat to supply district heating networks compared to the counterfactual scenario using air source heat pumps.

In particular, noting the selected South Humber synergy and the associated economic modelling, there is a technically and economically feasible project opportunity.

For the South Humber synergy is it noted that:

- To recover waste heat, minimal modifications to the green hydrogen production project is required.
- The project presented an attractive business case for both the hydrogen production and district heat network operators, with following key financial results:
  - For the hydrogen production operator: Projected IRR of 14%, with a positive NPV.
  - For the district neat network operator: Projected IRR of >4%, with positive NPV (compared with counterfactual scenario projected IRR of <1% IRR).

Additionally, in comparison with the counterfactual scenario using air source heat pumps, the South Humber synergy could:

- Reduce the heating cost to the consumers by approximately 20%; and,
- Reduce carbon emissions by over 50%.

Further, the economic modelling identified the following key sensitivities:

- Waste heat availability / heat demand;

[23] 'Future Energy Scenarios' (National Grid, July 2021). Available at: https://www.nationalgrideso.com/future-energy/future-energy-scenarios/fes-2021/documents

- CAPEX; and,
- Difference in waste heat and district heat network temperatures.

Consequently, these parameters / sensitivities were identified as biggest risks.

In addition to the above, the South Humber synergy includes wider benefits. These comprise:

- Public health benefits due to a reduction in electricity-related air emissions for hydrogen and district heat network projects, and over the 40-year lifecycle, the South Humber synergy could reduce the social cost of air quality impacts in Stallingborough by up to £2m;
- The potential to reduce fuel poverty by providing access to low-cost, low-carbon heat for communities adjacent to large-scale hydrogen production projects;
- A positive contribution towards improving energy security by reducing the electricity demand from the heating sector, and thereby reducing pressure on the National Grid Electricity Transmission System; and,
- Providing a positive contribution towards rolling out of offshore wind and large-scale hydrogen production projects by improving their financial performance, with associated positive socio-economic and supply chain benefits.

Therefore, the overarching conclusion of this Study is that significant economic, environmental and social benefits are associated with heat recovery from hydrogen production, and its auxiliary processes.

However, for such benefits to be realised, hydrogen production projects would have to be placed in close proximity to heat clusters. This not only provides an opportunity to develop local clean sources of hydrogen (with the potential to attract new businesses to the area), but also forms a key part of the decarbonisation of energy, and could significantly accelerate the UK's decarbonisation of heat.

The Synergy Study also concludes that waste heat recovery is possible from both blue and green hydrogen production. Whilst noting that the lower temperature of heat typically available from blue hydrogen production is likely to lower any financial returns, the overall project performance is expected to be better than the counterfactual scenario of heat pumps.

8.3 Recommendations

The main recommendation, given the significant environmental, economic and social benefits, is to carry out further and more detailed assessment of the synergy opportunities identified.

Additional key recommendations, to support the further identification and development of strategic synergy opportunities, are for:

- Local planning authorities to proactively promote and support hydrogen production and district heating / heat network synergies by developing guidance and requiring its consideration through the planning process (e.g. actively encouraging new hydrogen production infrastructure and district heating / heat network energy centre co-location);
- The UK and devolved Government and planning authorities to require offshore wind projects to locate onshore grid connections close to existing district heating / heat networks, associated energy centres and / or areas of high-density heat demand;
- The UK and devolved Governments to include a requirement, when assessing grant funding applications for hydrogen production projects, to consider the feasibility of heat recovery; and,
- The UK and devolved Governments to give consideration to making dedicated funding available for the development and delivery of heat recovery from hydrogen production projects.

The Synergy Study has also highlighted that early engagement of hydrogen production and district heating / heat network stakeholders is crucial for identifying, promoting and realising feasible synergies and, therefore, such early engagement should be encouraged and prioritised during the development of hydrogen production and district heating / heat network projects.

In this regard, the key recommendations, to support the further identification and development of individual synergy opportunities, are that the following steps should be taken during the early development stages of any project:

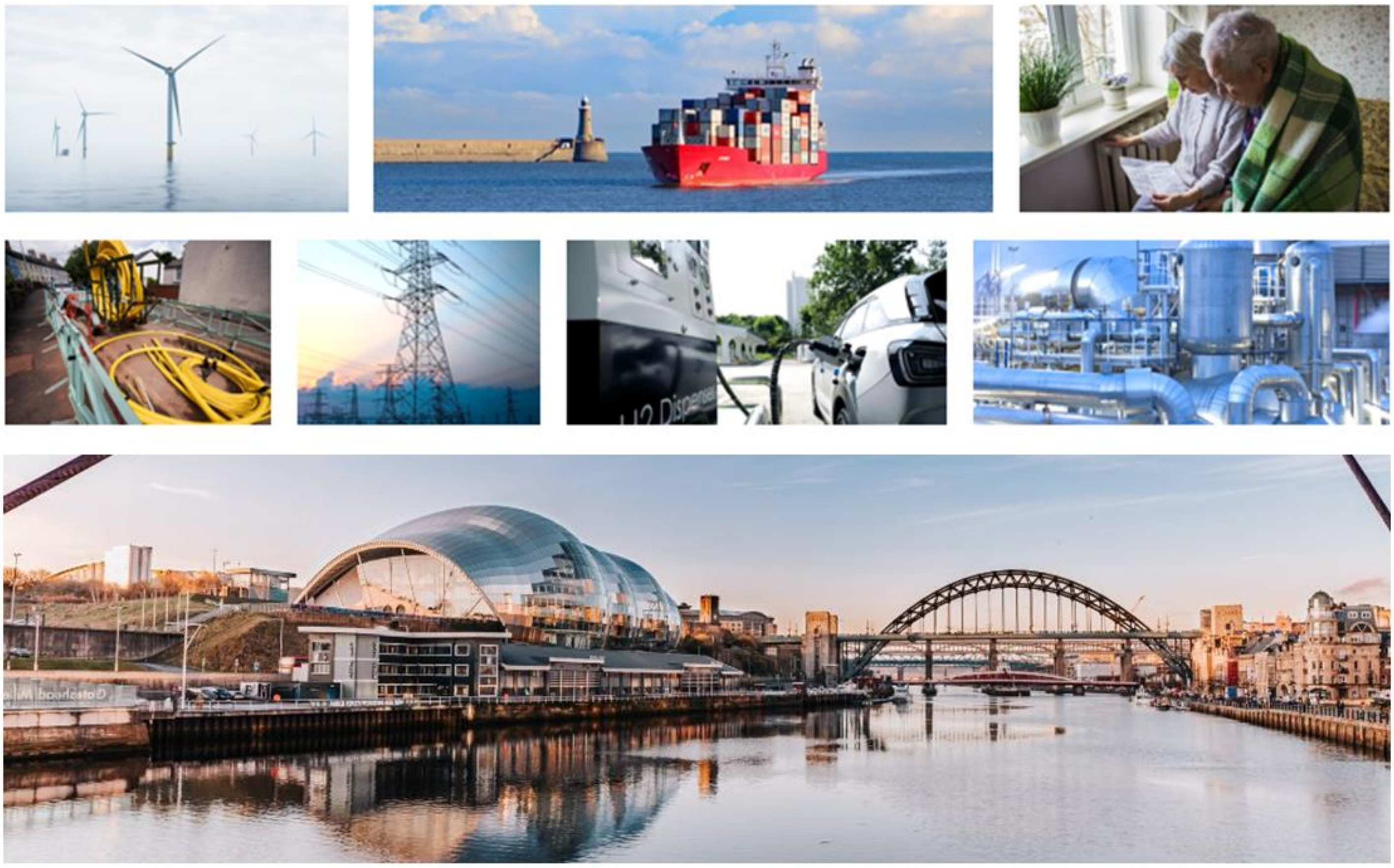
- For hydrogen production projects, practical options and associated business cases for waste heat recovery should be assessed / included within early feasibility and FEED (Front End Engineering Design) studies;
- For hydrogen production projects, ‘future-proofing’ for waste heat recovery (for example, by specifying electrolysers for cooling water temperatures suitable for heat networks and allowing sufficient space for the future addition of heat recovery equipment) should be undertaken;
- For heat network projects, waste heat recovery from hydrogen production should be prioritised in the implementation of the heat hierarchy;
- Where possible, hydrogen production projects and district heating / heat network energy centres should be co-located to reduce initial costs for any heat transmission network; and,
- Noting the conclusions, the key sensitivities (waste heat availability / heat demand, CAPEX and differences in wate heat and district heat network temperatures) should be addressed through early planning and engagement.

APPENDICES

The following Appendices are provided:

- Appendix A: Newcastle University Literature Review.
- Appendix B: Workshop / Webinar Summaries.

APPENDIX A: NEWCASTLE UNIVERSITY LITERATURE REVIEW



Review of Hydrogen for Heat Applications

A study of three locations within the UK for Ramboll

Centre for Energy 4/1/21 Newcastle University

Executive Summary

This report commissioned by Ramboll offers a preliminary appraisal of utilising heat by-product of H_2 electrolysis as a service with focus on key areas of the UK. The study includes: -

- a survey of existing H_2 projects in the UK
- available heat maps and knowledgebase on UK heating
- discussion on the merits of Hydrogen within future energy systems

A total of seventeen existing UK hydrogen research projects are outlined and can be categorised as

- first examinations of gas network repurposing for Hydrogen injection or blending,
- second post conversion whole system safety at network and home levels
- hydrogen as an industrial feedstock

Landscape

While a strong tradition of heat networks and district heating exists in Northern Europe, it has traditionally had a more limited role in the UK energy planning. Knowledge management and training, best practice guidelines and routes to deploy advanced technologies (i.e. GIS[1]-enabled trenching for distribution pipework and low cost HIU[2]) are areas that require ongoing work and research to make extensive heat networks more economically viable in the UK. Otherwise significant financial support is required to make them an option in future UK energy systems. While economic dynamics will be different where H_2-based cogeneration of heat and power is examined, the results will remain highly sensitive to the overall process efficiencies, cost of feedstock, retail price of heat and CapEx of required infrastructure. The literature consulted for this report converge on suggesting significant upfront investments.

A wide range of values for overall thermal demand in the UK was found with lower and upper bounds of 86 and 183 kWh/m^2/yr. of end-use thermal demand in domestic sector. Characterising UK domestic thermal demand is an ongoing effort with accelerated insights generated from rollouts of smart meters. Several online tools depicting UK heat map are outlined in this work with varying levels of resolution that in one instance is down to property level.

Some of the recent work in scientific community suggest change of total thermal demand, peak demand and ramp rates as a function of widespread fuel switching. This for instance implies a switch from natural gas boilers to district heat from hydrogen will not retain the profile and magnitude of the aggregated gas boiler systems in targeted areas and hence historical data can only serve as a broad guiding star than a predictor of thermal demand from a centralised hydrogen production facility.

[1] Geographic Information System

[2] Heat Interface Unit

Contents

1. About this report

Newcastle University Centres of Research Excellence

The Newcastle University Research Strategy sets the ambition for the growth of people and resources to deliver important research missions through a growing portfolio of **Newcastle University Centres of Research Excellence** (NUCoREs). The Centres of Research Excellence:

- set a visibly leading mission and strategy for our collective research activities
- catalyse the way we work together across disciplines and with external partners
- provide a venue that gives researchers the freedom and opportunity to succeed
- coordinate our response to the world's major challenges

The NUCoREs contributors benefit from drawing upon all the resources of the University. They have built teams that are diverse in career routes and career stages. They also focus on disciplinary background and protected characteristics.

Centre for Energy

Launched in October 2019, the **Newcastle University Centre for Energy** was the first of these centres. Building on Newcastle University's significant portfolio of Energy Research, the Centre provides strategic focus with our governmental, industrial and third sector partners to tackle the global need for a rapid transition to clean affordable energy.

The Centre is led by Dr Sara Walker, Reader in Energy at Newcastle University supported by an executive team of leading academics and researchers from the Energy research field.

About this Project

Ramboll, a multi-disciplinary engineering, design and consultancy company commissioned researchers at Newcastle University's Centre for Energy to assist their investigations into the opportunities within the UK for utilising hydrogen to meet the UK's heating demand.

With a focus on existing, planned and potential hydrogen generation and/or production projects; and existing, planned and potential heat projects (e.g. networks and opportunities), the research team have been asked to deliver a literature review and an initial appraisal of the key projects and stakeholders within each of the three specific cluster areas. This work will inform Ramboll's stakeholder engagement planning for their future work in this area.

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2. Research Introduction

i. Background and context

On the 18th of November 2020 the UK government announced its 10 point plan for a Green Industrial Revolution. In point 2 of this plan they outlined Driving the growth of low carbon hydrogen, which included a target of 5 GW of low carbon hydrogen production capacity by 2030 and industrial 'SuperPlaces' built around renewable energy, carbon capture and storage (CCS) and hydrogen. They estimate the creation of 8000 jobs by 2030 potentially growing to 100,000 by 2050. £240m will be available through a Net Zero Hydrogen fund. ("The ten point plan for a green industrial revolution," 2020).

The UKERC briefing on "The pathway to net zero heating in the UK" (Rosenow et al., 2020) states that there is some uncertainty in how heating might be decarbonised, but it sets out some potential pathways to achieve this. A "combination of energy efficiency, heat pumps and district heating is the least-cost technology pathway for heat decarbonisation in the next 10 years". Regarding the use of low carbon hydrogen in the gas grid the report states that "the idea appears to have gained some traction as an option with UK policymakers". Various active industrial demonstrations projects such as H21, H100 and HyNet will assess the viability of this approach. The UKERC analysis, using the TIMES MARKAL model suggests that district heating will have a significant role to play which increases with the emissions reductions that are met, see Figure 1.

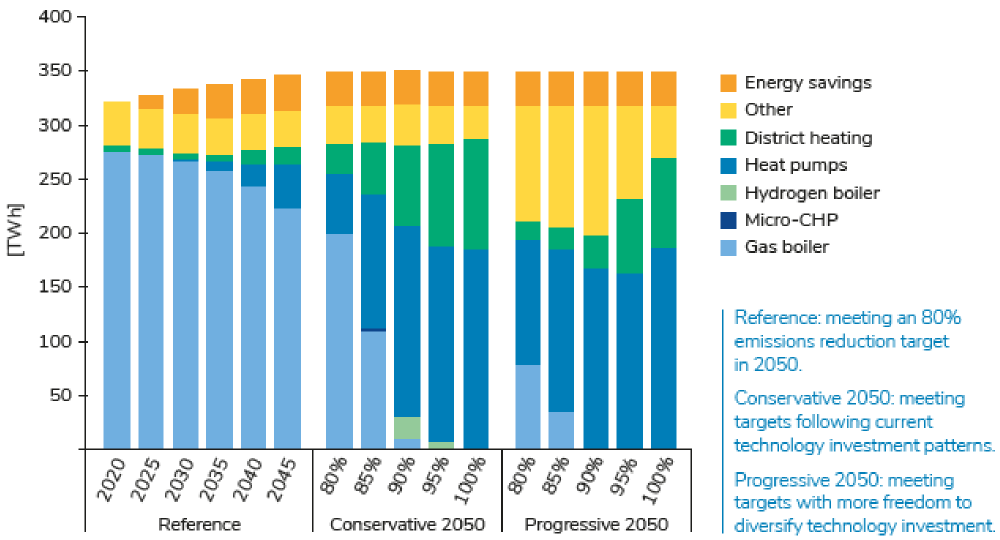

Figure 1 Heat technology change under different targets (Rosenow et al., 2020)

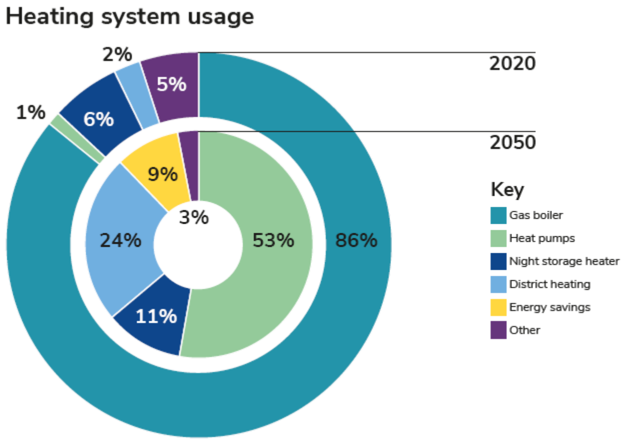

Figure 2 Heating system usage (Rosenow et al., 2020)

ii. Current landscape

Hydrogen can be a socially and technically acceptable low carbon solution particularly due to no direct CO2 emission and its ability to act across multiple energy vectors and multiple industries. While retails price of hydrogen per unit mass or volume remains several order of magnitude larger than comparative fossil fuel replacements (Dawood, Anda et al. 2020, Khouya 2020), it is generally accepted that scaling up of production is the biggest driver of Hydrogen cost reduction (followed by the supply chain improvement). The last IEA report on the global production of hydrogen stated the annual production in 2017 was approximately 60 Mt (IEA (2020)). Currently most of the hydrogen produced globally is heavily reliant on fossil fuels, with a staggering 96% of hydrogen derived from technologies that reform fossil fuel feedstock (Fakeeha, Ibrahim et al. 2018). The proportion of Hydrogen derived from electrolysis technologies currently stands at around 4% yet is predicted to rise as a function of global interest in green hydrogen.

iii. Comparative cost of Hydrogen production

While a wide range of values exists on retail price of hydrogen, as a comparative measure some of the lowest values reported in literature are outlined here. Respective non-renewable Hydrogen retail price from coal, natural gas and nuclear has been as low as $0.27/kg (advanced gasification with sequestration of coal)(Gray 2002), $1.7/kg (conventional steam methane reforming)(Chisalita and Cormos 2019) and $1.75/kg (Sulphur–iodine thermochemical in modular Helium nuclear reactors)(Richards, Shenoy et al. 2006). However renewably generated hydrogen has understandably much greater retail price with recent figures ranging from $2.4/kg (biomass gasification)(Sentis 2016), $7.1/kg (electrolysis from wind) (Dinh, Leahy et al. 2020) and $5.57 /kg for solar PV assisted electrolysis (Touili, Alami Merrouni et al. 2020). The retail price is extremely sensitive to economies of scale and plant yield, and reasonably sensitive to economic forecasting (future inflation considered as discount factor). It is worth noting that a range of 8% to 25% has been reported on Internal Rate of Returns (IRR) of Hydrogen retail price studies across years 1998 to 2020 (Bartels, Pate et al. 2010, Fakeeha, Ibrahim et al. 2018, Khouya 2020), which reflects the diversity in the economic landscape of host countries. This makes comparative assessment of economic studies difficult yet the magnitude of difference between renewable vs. non-renewable hydrogen demonstrates the challenge of making green hydrogen economically feasible. However the following innovations offer the opportunity for renewably derived hydrogen to decline in future:

1. Solar resources: Historically the median price of PVs for residential installation has been around £4.5/W of peak installed capacity with similar figures reported for system installations at larger scales. However thin film PVs are under development and some are available on the market for as little as £0.75/W of peak installed capacity. This can fundamentally change the economics of hydrogen retail price (Haegel, Atwater et al. 2019); however, the Northern parts of England and much of Scotland has a lower annual solar yield potential than those achieved in – for instance – the southern European context.

2. Wind power: The mean cost of medium to large size wind farm installations in Europe was reported at £1500/kW of installed capacity, with offshore installations costing twice as much (IRENA 2012). There is no perceptible trend in the cost reduction of onshore wind turbine design, deployment and operation, however offshore deployment has observed reductions at magnitudes of around 30% which may continue into future with improved engineering techniques.

3. Biomass: deriving hydrogen from biomass contains multiple processes that are both thermochemical (pyrolysis or gasification) or biological (direct or indirect bio-photolysis, biological water-gas shift reaction, photo fermentation and dark fermentation) (Bartels, Pate et al. 2010). Future trends in how biomass economics can alter in Britain require detailed technical knowledge of these processes and the availability of skills and resources in the region.

It is difficult to overemphasise the fact that hydrogen production is a well-established industrial exercise and the main research challenge is low or zero carbon H_2 production at scale and in an economically viable manner. This combination will allow minimising the cost of decarbonisation using hydrogen as an active component of the energy system, and while a large number of vernacular, location specific and project specific considerations act to inform the best pathways, it is on a cost, energy and exergy efficiency that future hydrogen production technologies need to compete.) . These KPIs were examined against a backdrop of 19 separate H_2 production procedures which identified the hybrid nuclear thermo-chemical cycle to have the highest rating. Photo-electrochemical and PV based electrolysis were least comparative when assessed across all KPIs (Dincer and Acar 2015).

iv. Hydrogen storage credentials

On its own, hydrogen is challenging to store and transport. This has led to a wide range of research that investigates multiple organic compounds, such as commercially available ammonia (NH_3), as an intermediary for storing and transporting H_2. Ammonia's density (674 g/l) offers advantages over storing H_2 (71 g/l). Although ammonia is currently produced under 200 bar at 400˚C and requires a catalyst, it may be renewably manufactured in future (Lamb, Dolan et al. 2019). For organic H_2 carriers active areas of research are the development of a catalyst system that allows hydrogenation and dehydrogenation of the carrier, and the identification of mediums with high gravimetric capacities for hydrogen (Shimbayashi and Fujita 2020).

Without a medium, hydrogen must be stored at either high pressures (700 bar and above) or be liquified to enable storage with reasonable facilities. While in gaseous form, H_2 has a small mass density and is outperformed by other fuels, while in liquified form it can be an excellent energy carrier as per kilogram it nearly contains 3 times as much energy (33.3 kWh/kg) as equivalent petrol or diesel (12 kWh/kg).

H_2liquification requires substantial amounts of energy due to very required temperatures (about -253℃). Liquification can claim up to 36% of imbedded energy of H_2 and hence an active area of research is the optimisation of this process (IDEALHY project 2021).

v. Hydrogen as a low carbon heating solution

If replacing natural gas as a heating and domestic hot water fuel, the properties of hydrogen need to be contrasted to natural gas to inform the required appliance adaptation. This is currently being investigated both by manufacturers of household appliances (both the new appliances required to utilise hydrogen, the adaption of existing appliances and the potential for dual-fuel appliances that can switch between hydrogen and natural gas). Hydrogen burns with a greater flame velocity than natural gas and has a nearly colourless and odourless flame. This is the principle challenge in both the development of hydrogen only as well as dual fuel appliances (de Vries and Levinsky 2020) . As a result, research communities are developing new approval and regulation standards for avoidance of flashback risk in hydrogen appliances. A report commissioned by the UK Government recommended an initial phase of hydrogen only appliances (as opposed to dual fuel appliances) to bring about a safe hydrogen age and concludes that the government intervention in the market is required to enable this transition of fuels to be undertaken safely and successfully (Frazer-Nash Consultancy 2018).

vi. Heat as a by-product of Hydrogen production

Co-generation of heat and power is a long-standing tradition in energy system planning for both the built-environment and industrial applications. However, the utilisation of heat from a hydrogen production facility (referred to as valorisation of heat in scientific literature) still remains a science and economics challenge. Industries with the potential of producing high temperature gas or liquids as a by-product of their core process has traditionally been looking at ways to improve their process efficiency by recovering surplus heat. This for instance been researched heavily in steelworks (Zaccara, Petrucciani et al. 2020) and Nuclear power plants (Xu, Dong et al. 2017) where typically surplus heat is available at temperatures of around 800–1000°C which indeed in itself is high enough to enable H2 production too. Therefore there is a wider scope of scientific literature that examines the recovery of the high temperature heat to generate steam for hydrogen production in sustainable processes such as polymer electrolyte membrane electrolysis, solid oxide electrolyze cell electrolysis, and biomass gasification.

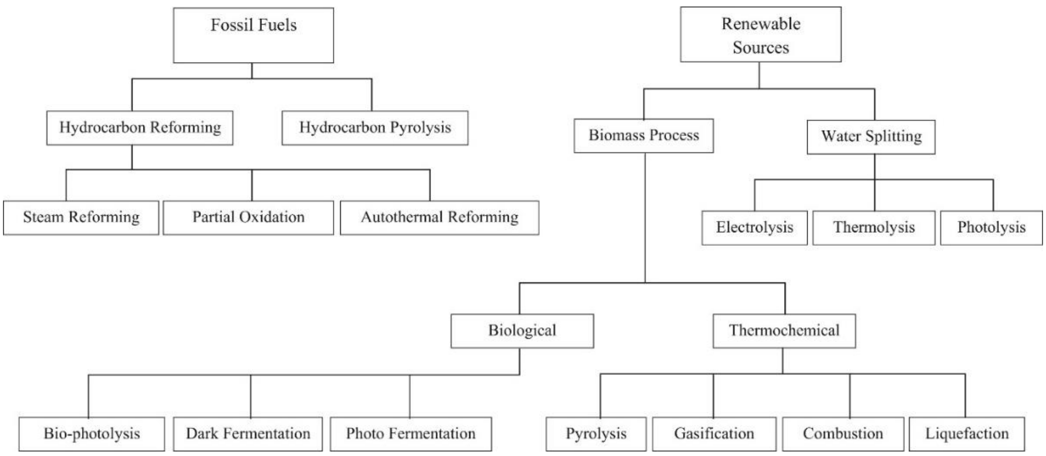

Figure 3. A breakdown of hydrogen production methods (reproduced from (Nikolaidis and Poullikkas 2017)). With the exception of biological processes, all other methods produce medium to high temperature process heat.

It is important to note that both electricity and heat supplies are required for the main two types of electrolyser based H2 production; PEM and SO. Alkaline electrolysers that forms the third electrolyser type also requires heat but normally to a lesser extent than PEM and SO types (see table 1). This by definition means that removal of heat from the process will results in a lower operational efficiency as for instance at 2500°C the process of hydrogenation from water does not require any power since at such high temperatures hydrogen and oxygen are separated through thermal decomposition of water. Proton Exchange Membrane Electrolyser Cells (PEMFCs) are, for example, 10% to 20% more efficient if electrolyser temperature is elevated. Similarly, Solid Oxide electrolyser Cells (SOECs) that require higher temperatures than PEM deliver improved efficiencies at higher temperatures. Therefore, where the prime fuel for electrolysis is electricity, the removal of heat from the process lowers H2 production efficiencies.

Table 1 Main features of the three prominent electrolyser technologies

(Ref: (Alaswad, Palumbo et al. 2016), (Sheffield, Martin et al. 2014))

Electrolyser Type	Operating temperature (°C)	Electrical efficiency (%)	Application	Notes
High Temperature PEM [a]	110-180	50–60	Transport, energy storage, oxygen for life (submarine/aircraft).	Lower power consumption and smaller than Alkaline, higher purity of H_2, low ecological impact.
Low Temperature PEM	60–80	40–60	As above	As above
Alkaline	~100[c]	60	Military and space.	Operates at the lowest temp, has more range of component material and has a quicker start-up than other technologies.
Solid Oxide	500–950	>60	Energy storage, Utility scale energy systems.	Normally requires a source of high temperature heat (nuclear power).

Notes:

[a] Proton exchange membrane

[b] Uninterruptable power supplies

[c] While typically at 100°C, research also reports on demonstrators operating at up to 400°C.

There is a relatively new scope of literature that examines the production of H_2 from excess process heat. This for instance involves recovering geothermal heat (Yilmaz, Kanoglu et al. 2015)(at 200°C) or CHP plant heat (at temperatures capable of producing steam (Boardman 2021)) to respectively produce hydrogen at rates of 0.498 g H2/kg of geothermal water (at an exergetic unit cost of $3.14/kg H_2) or 0.647-1.27 g H_2/kg of steam from CHP plant (at a cost of \$3.06/kg of uncompressed H_2, \$4.11/kg of H2 at 350 bar or of \$16.53/kg of liquified H_2).

Biomass driven hydrogen production facilities will also involve substantial amount of thermal exchange as most biomass stocks contain substantial amount of hydrogen. However, biomass-derived H2 from biological processes are slow and inefficient, and thermochemically derived H_2 from biomass are inefficient, costly and require extensive facilities design. Opportunities exists for heat recovery from a biomass-based H_2 production facility as the main subcategories operate at the following temperatures:

1. Gasification and reforming: This process requires a high temperature reactor normally maintained at 700-1400°C (Shen and Fu 2018).
2. Microbial processes: These involve enzyme-assisted fermentation of biomass with or without the assistance of natural light with operational temperature range being 30-80°C (Mishra, Krishnan et al. 2019).
3. Low temperature electrochemical process: This approach is the most advanced of all three main categories and involve biomass electrolysis for hydrogen production (BEHP) at temperatures below 100°C (Liu, Liu et al. 2020).

The third category remains of the greatest interest to the scientific community as this process replaces the needs for high temperatures needed in the first category (gasification/reforming) and also resolve the high electricity requirement of electrolysis (about 4.5–5 kWh per cubic meter H_2 consumption to split water). Biomass in the third process acts as a hydrogen and electron donor and reduces both water and electricity consumption. Clearly the opportunity to recover low grade heat from all processes exists but this will impact on the process efficiency as in all three categories heat itself is the main engine for the excitation of the process.

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3. UK Heat Maps

Unlike electrical demand, heat demand either in domestic, commercial or indeed industrial sectors are poorly mapped and understood in the UK. However, attempts have been made in more recent years to address this issue in particular in light of UK stringent decarbonisation targets and the need to replace fossil-fuel heating. This has been particularly aided through smart meter data in the last decade.

Initial analytical results of smart meter data show that domestic heat demand in the UK is highly diverse despite its relatively modest size as a function of a multiplicity of climatic and demographic diversities that the country has.

i. Domestic heat demand

The scientific literature reporting on the widest pool of available smart meter data concerns a 2020 publication by the University of Strathclyde that includes smart meter and gas data from 253,931 flats, and while the number of other property types were not reported by the authors it is likely to be in the region of hundreds of thousand samples as this work utilised openly available BEIS sourced from sub-national electricity and gas consumption meter data [1]. The used dataset ranged from 2016 to 2019 and given that by the end of March 2020 a total of 15.5 million smart meters were operating in homes across England, Scotland and Wales, the sample size is likely to run into millions of homes too. As illustrated in Fig 1, the annual heat demand consumption for dwellings with electrified heating is considerably lower than those using natural gas (which remains the prominent heating type). It is also interesting to note that the range and median of annual electrified heating type changes only very modestly as a function of property type which indicates that electrified heating types are governed closely by a budget cap, whereas where homes are heated by natural gas a notable change follows in range, quartile and median of heat demand as a function of property architype.

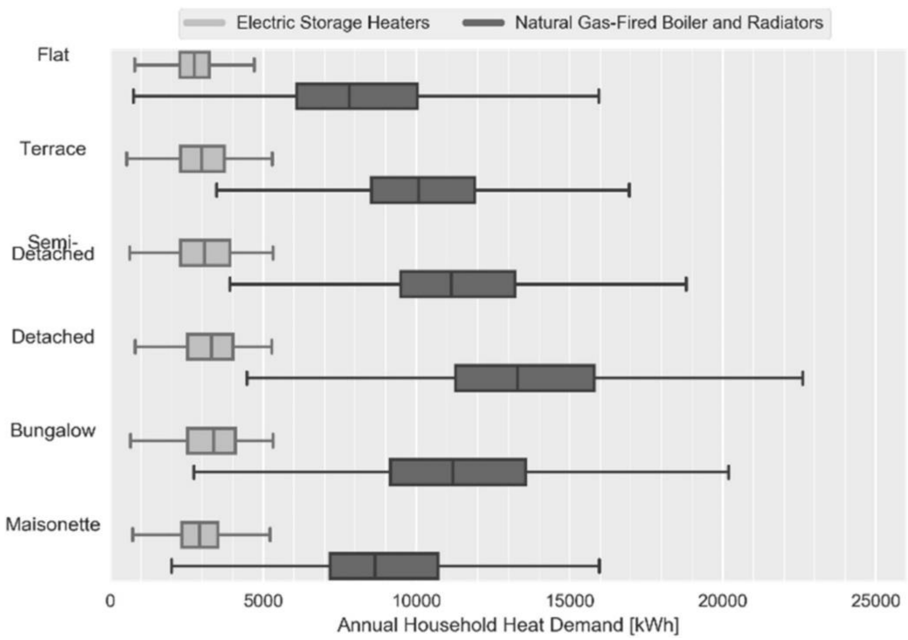
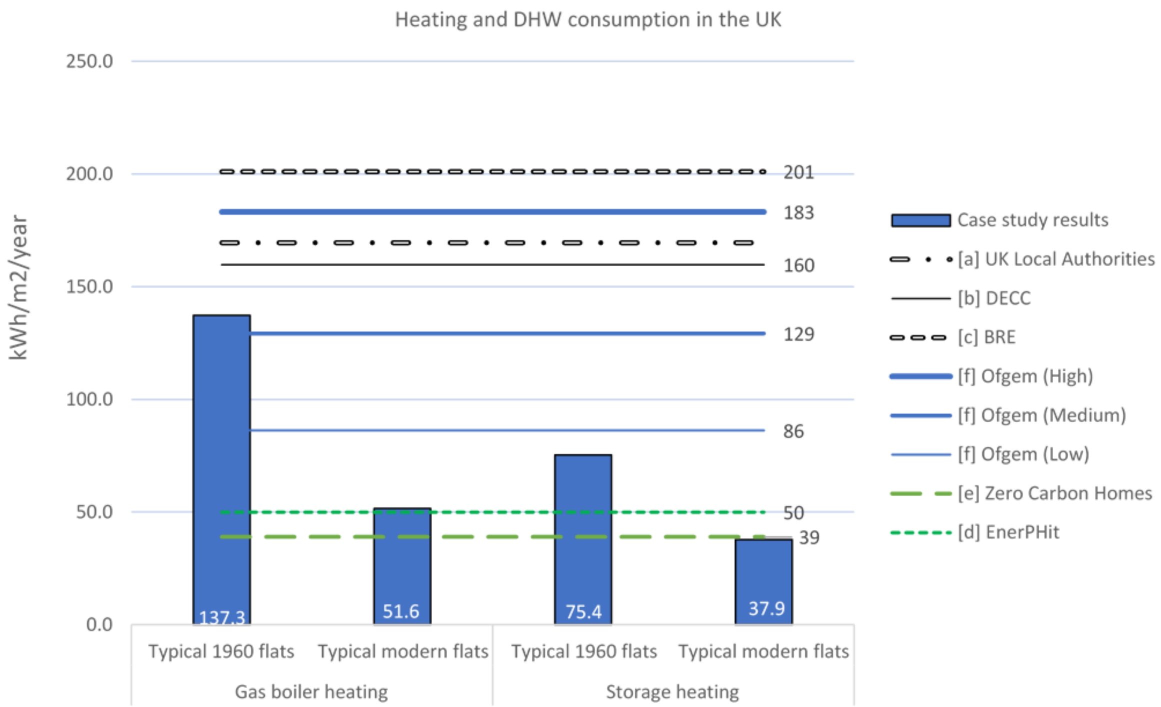


Figure 4. Distribution of UK annual household heat demands by dwelling and main heating type. Demands are derived based on gas and electricity meter consumption data averaged over the years 2016 and 2017 (reproduced from [1]).

One study [2] where a broad number of thermal heat demand studies and best practice guides in the UK are united to characterise UK heating and domestic hot water consumption is represented here in Fig. 2. This work summarises results from multiple sources where data samples range from pools of 500 to 700 properties , to 7370 and more broadly nationwide empirical values. The field data results are benchmarked against best practice guides such as Passivhaus and Zero Carbon Home guides. Medium empirical value for UK domestic thermal demand (i.e. DHW and heating) range from 86 kWh/m^2/year to 201 kWh/m^2/year. While this variation is inevitable given the diverse UK architype and microclimates, uncertainties in property sizes, fuel conversion efficiencies and metering accuracy result in a wider than expected spread. Ofgem data with a nationwide source of empirical values states the lower bound of thermal demand in the UK to be 86 kWh/m^2/yr., the medium 126 kWh/m^2/yr. and the upper threshold of 183 kWh/m^2/yr. Best practice guides such as EnerPHit set a threshold of 50 kWh/m^2/yr. (this is for retrofitting existing properties using Passivhaus guide. A lower threshold of 39 kWh/m^2/yr. is suggested by Zero carbon homes.



Footnotes:

[a] Measured energy consumption in local authority properties (n= 500-700 households) [5].

[b] DECC (Department of Energy & Climate Change) 2013 temperature adjusted UK average gas and electricity consumption [6]. Area-weighted for average UK domestic property size of 90m^2 [7] with 3% discounted to account for cooking (n= Nationwide).

[c] BRE (Building Research Establishment) stock characteristics of average UK household gas consumption [8], area-weighted and adjusted for cooking as per [b] (n= 7370 households).

[d] The EnerPHit standard - a Passivhaus best practice combined heating and cooling target for retrofit projects [9].

[e] Zero Carbon Hub 'combined heating and cooling' to benchmark a zero-carbon flat [10].

[f] Ofgem (The Office of Gas and Electricity Markets) typical domestic consumption values in 2017 (similar treatment as [b]) [11].

Figure 5. Benchmarking of standardised domestic thermal demand (kWh$_{th}$/m^2 of habitable space/yr.) for typical 1960s vs. modern flats against existing field data and best practise guidelines.

ii. Interactive heat maps

There are currently few UK and EU funded heat mapping tools and online resources that aim to provide heating and cooling network analysis and feasibility options. A wide range of applications are suggested for these tools that in short include optimum heating network design specifications, resource and demand matching, and existing district heating expansion plans. The following table outlines some of these tools that cover Both the UK and wider European league of nations. It is worth noting that some of these tools remain in the development phase with increasing levels of sophistication and granularity offered with progressing time.

The following table outlines some of the interactive resources that are available for decision makers to assess a GIS-based map of thermal demand in the UK.

Table 2 Interactive online heat map resources offering aimed at planning, feasibility and district energy system design studies.

Resource	Service (and cost)	Main Function	link
Thermos	Heating and cooling map (free at basic level, fee-based for advanced projects)	District energy planning and optimisation	www.thermos-project.eu/thermos-tool/what-is-thermos/
National Heat Map[1] by The centre for sustainable energy (CSE)	Address-level heat demand data (free at basic level, fee-based for advanced projects).	New web-based tool to support low-carbon energy project	www.cse.org.uk/projects/view/1183
Hotmaps	Heat density at multiple layers with the ability to segment into required levels. (Free).	The open source mapping and planning tool for heating and cooling	https://www.hotmaps-project.eu/ with the map available at https://www.hotmaps.eu/map
PlanHeat	Yearly and hourly heating, cooling and Domestic Hot Water (DHW) demand from different typologies (Free).	Planning of alternative, low carbon heating and cooling services	http://planheat.eu/
Local Energy Area Representation (LEAR) from ESC [2]	Static maps of district heating and power demands (Fee-based)	Planning, feasibility and whole system research studies	https://es.catapult.org.uk/comment/local-energy-asset-representation/

Notes:
[1] This service was combined with Thermos in 2018 although CSE retains a fee-based service.
[2] Energy System Catapult.

It is worth noting that there is a range of publication in the scientific literature whereby historical data of heating (or/and power) demand from specific local authorities in the UK have been selected to create district level heat maps and demand intensity guides. The results are often used to assess low carbon supply options, and to propose new and novel methodologies for future energy system planning. Such studies however tend to be location-specific and while historical data might be available as a part of literature submission, these reports rarely offer a decision support tool to the practitioners in the industry [3]. Once recent example is outlined below where a natural gas price of over 5p/kWh was found to be essential for driving heating technology uptake away from gas boilers, and the current mix of heating technologies was also reported to be unable of providing end-user thermal demand at a carbon intensity of 180g/kWh as was suggested by CCC.

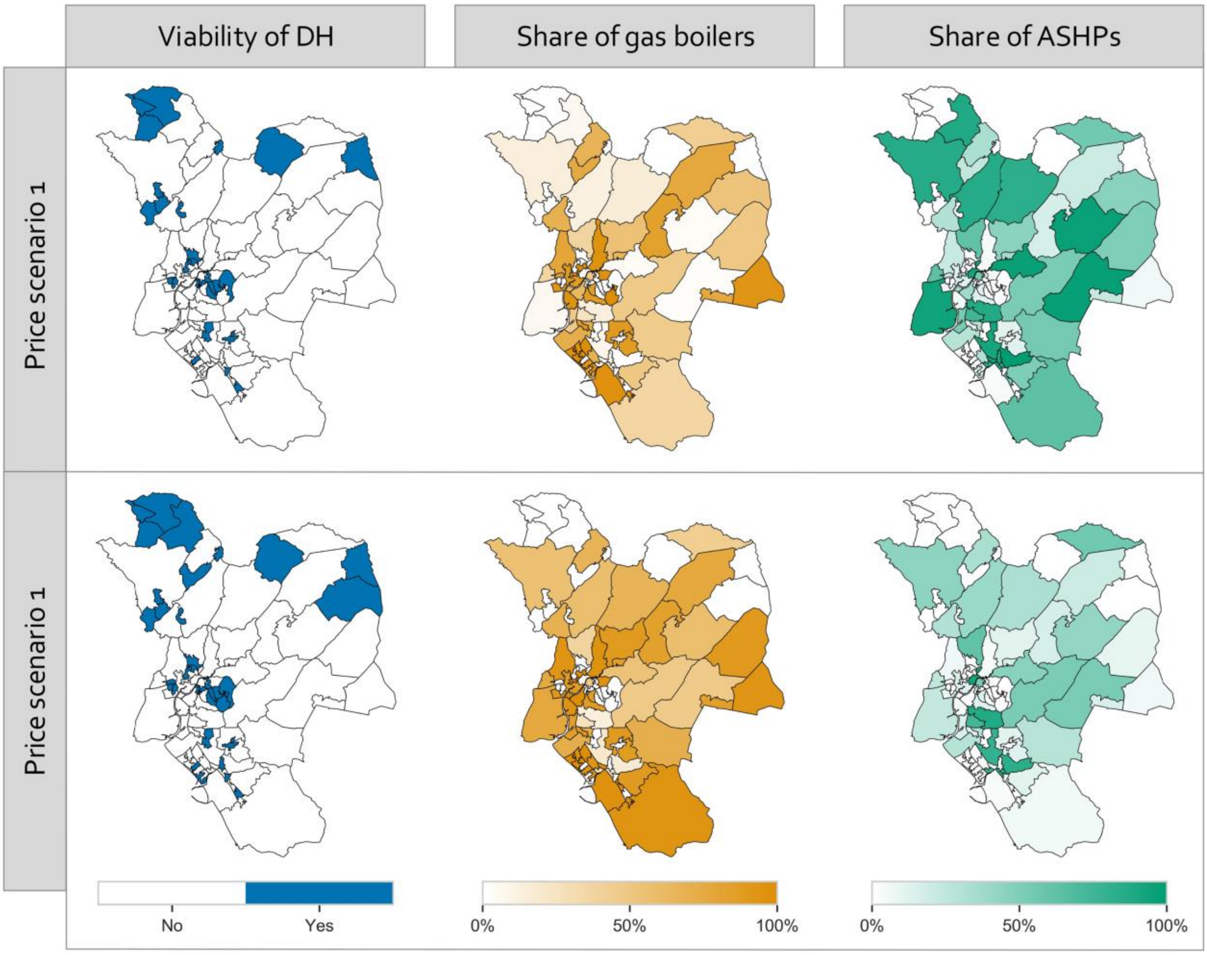


Figure 6 Possible heating technology uptakes in Neath Port Talbot districts as a function of prices scenarios 1 (Electricity 14.5 p/kWh- Gas 6 p/kWh) and 2 (Electricity 19.5 p/kWh- Gas 7 p/kWh) [reproduced from [4]).

It is clear that a much richer map of heat demand will emerge in the coming years with advancing smart meter infrastructure and data analytics applied. Heat maps are currently dominated by static reports of historical data. A doubling of heat demand is suggested to literature where electrified storage heating may be replaced with technologies with operating costs similar to Natural Gas fired heating. This suggests that if heat recovery from H_2 production can deliver heat as a service with equivalent unit price as that of natural gas, a substantial increase in heat demand is likely to be observed where storage electrified heating is displaced.

While the figures and online resources provided in this chapter can offer a nominal guiding star on the shape, spread and magnitude of thermal demand in the UK, parts of the scientific community believe that they offer a limited view of future horizons as climate change and fuel switching to low carbon sources are likely to result in drastic changes in how thermal demand will persist in the UK [12].

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4. Summary of proposed and ongoing hydrogen projects

This section summarizes proposed and ingoing hydrogen projects. With the exception of *H2-Heat,* the search did not uncover evidence of projects undertaking heat recovery from Hydrogen generation. The *H2-Heat* project focus is on using waste heat from heat-intensive industrial processes such as steelworks, refineries, glass, cement, to mention a few, using metal hydride heat pumps. Whilst this project will investigate the use of these heat-pumps alongside long distance hydrogen and heat transport, it does not explicitly mention heat recovery from hydrogen generation.

i. Dolphyn

Project Name	Dolphyn
Stakeholders and Partners	ERM, NEL (https://nelhydrogen.com/), Doosan, Offshore Design Engineering (ODE), Tractebel Engie, Principle Power Inc. (PPI)
Expert Advisors	Lloyd's Register
Funding	BEIS Hydrogen Supply Competition Phase 2
Contact Email	freddie.hospedales@erm.com
Website	https://ermdolphyn.erm.com/

The Dolphyn (Deepwater Offshore Local Production of HYdrogeN) project consists of a 2MW floating offshore wind-farm with (green) hydrogen production, located off the coast of Aberdeen. This is the first application of this technology at this scale.

The proof of concept (Phase 1) is complete. Phase 2 was due to make a final decision on investment of the 2MW prototype by March 2021. The aim is to have a 10MW system running by 2027.

The platform will use desalination plant and electrolysis to convert sea-water to hydrogen on the floating platform, using energy from the wind turbines.

ii. Gigastack

Project Name	Gigastack
Stakeholders and Partners	ITM Power, Ørsted, Phillips 66
Expert Advisors	Element Energy
Funding	BEIS Hydrogen Supply Competition Phase 2
Contact Email	gigastack@element-energy.co.uk

Website	https://gigastack.co.uk/

Gigastack will use ITM Power electrolysers to demonstrate bulk transport of low/zero carbon hydrogen to Phillips 66 Humber refinery. The system aims to use electricity generated by the Hornsea windfarm.

There are three phases to the project. Phase 1 was a feasibility study that: developed designs for a 5MW electrolyser; explored the synergies between the offshore windfarm and production from the electrolyser; and a market study based on 100MW electrolysers. In phase 2 Phillips 66 and ITM are working on the 100MW electrolyser design and integration with the refinery and trialling equipment for the manufacturing the 5MW system at scale, as well as developing work from phase 1. Phase 2 is due for completion in mid-2021. Phase 3 will seek to deploy a larger electrolyser in the Humber, dependent on the results from phase 2.

iii. Humber Zero

Project Name	Humber Zero
Stakeholders and Partners	Humber Industrial Cluster Plan (Humber Refinery Phillips 66, Uniper, VPI-Immingham, Immingham Port, North Humber Industry and Docks, Easington Gas Terminal, other industry, Gas Network, Offshore wind farm, Saline Aquifer
Expert Advisors	Wood Group, Imperial College London and the University of Sheffield
Funding	Innovate UK's Industrial Strategy Challenge Fund
Contact Email	gigastack@element-energy.co.uk
Website	https://www.humberzero.co.uk/

Humber Zero is a project to reduce carbon emissions from industry. Humber Zero aims to decarbonise eight million tonnes per annum of carbon dioxide (CO_2) emissions, with the potential to target a further thirty million tonnes of CO_2 emissions from the wider Humber industrial cluster to the west of Immingham.

It plans to achieve this by integrating carbon capture storage, alongside green and blue hydrogen production into these existing, co-dependent industries. It will decarbonise local industry and provide hydrogen power for over 1 million local homes.

Humber Zero plans to use a combination of CCS technology and hydrogen production within an existing industrial cluster to decarbonise the wider Humber. It will integrate CSS technology into some of the industrial processes at combined heat and power plant VPI Immingham and the Phillips 66 Humber Refinery.

Post combustion CO_2 is captured at the source and then transported via pipeline either to CO2 storage fields in the North Sea or exported to international markets from the port of Immingham.

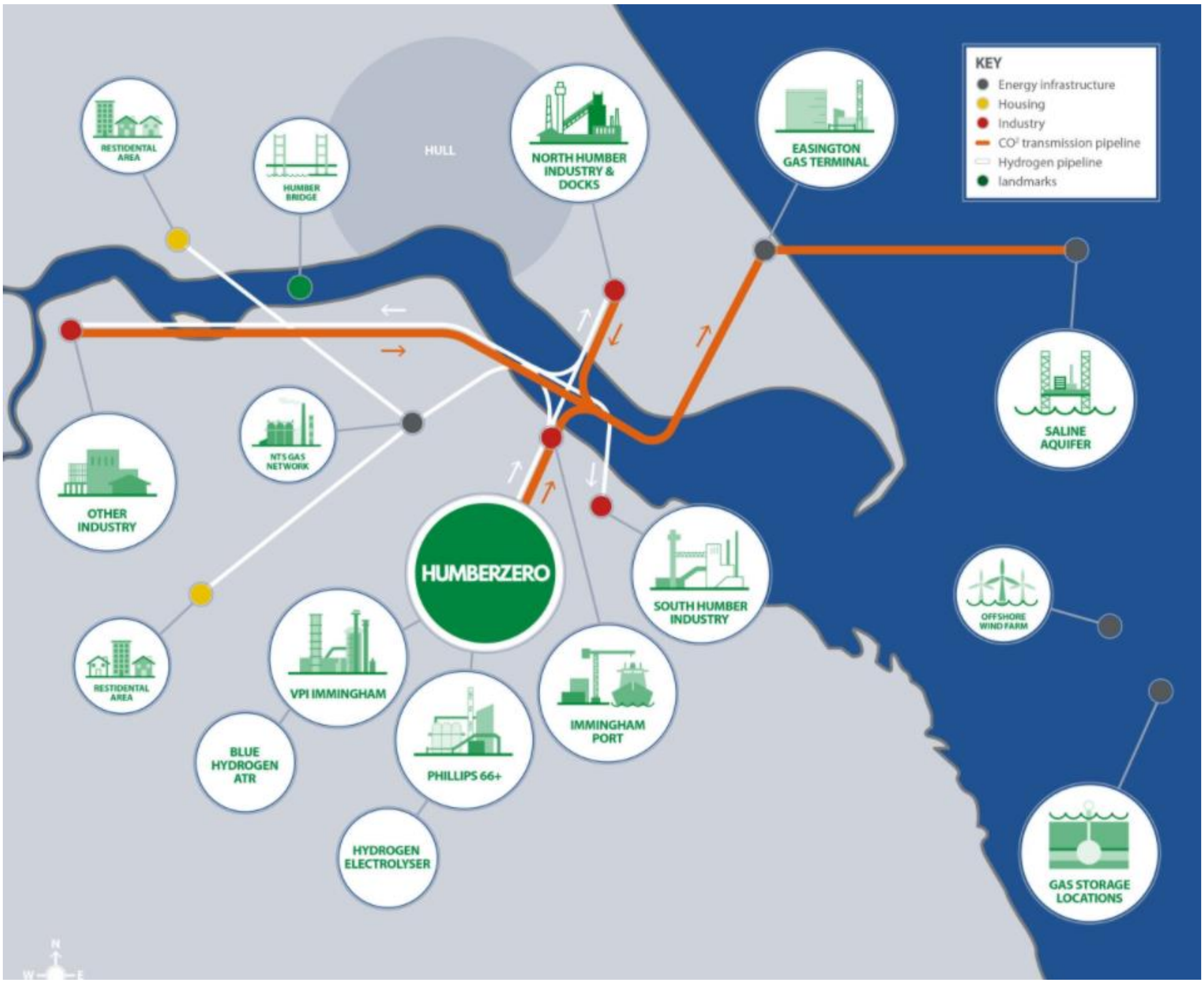

Figure 7 Humber Zero Project

iv. Green Hydrogen for Humberside Project

Project Name	Green Hydrogen for Humberside Project
Stakeholders and Partners	ITM Power
Expert Advisors	Element Energy
Funding	Innovate UK's Industrial Strategy Challenge Fund
Contact Email	Andy Allen, Finance Director, ITM Power, +44 (0)114 244 5111

Website	https://www.itm-power.com/news/green-hydrogen-for-humberside-project-deployment-study

On 16th April 2020, ITM Power announced that they and Element Energy had won a first stage deployment project in the UK Government's Industrial Strategy Challenge Fund competition "Decarbonisation of Industrial Clusters" to assess the feasibility and scope of deploying green hydrogen with some major industrial partners in Humberside.

> *The "Green Hydrogen for Humberside" will lead to the production of renewable hydrogen at the Gigawatt (GW) scale distributed to a mix of industrial energy users in Immingham, Humberside. Decarbonisation of this cluster is critical in reaching the UK's legally binding 2050 net zero emission targets. Humberside, the UK's largest cluster by industrial emissions, (12.4Mt of CO2 per year), contributes £18bn to the national economy each year and has access to a large renewable resource from offshore wind in the North Sea ("Green Hydrogen for Humberside Project Deployment Study,")*

v. Zero Carbon Humber (ZCH)

Project Name	Zero Carbon Humber
Stakeholders and Partners	12 formal partners – led by Equinor with public support from over 50 other international, national and regional organisations
Expert Advisors	University of Sheffield AMRC
Funding	Innovate UK's Industrial Strategy Challenge Fund
Contact Email	Equinor – eseri@equinor.com, tel. +47-958-82534
Website	https://www.zerocarbonhumber.co.uk/

Zero Carbon Humber is a £75m project part funded through Phase 2 of the Industrial Decarbonisation Challenge (which is part of the Industrial Strategy Challenge Fund) It also has significant financial resources from private companies within the consortium. It will develop a hydrogen pipeline, carbon pipeline and carbon capture and storage as shown in Figure 8.

The ZCH anchor project is Hydrogen to Humber (H2H) and is led by Equinor (formerly Statoil), ("H2H Saltend - Growing blue hydrogen in the UK - equinor.com," n.d.). This project will develop the world's largest hydrogen production plant with carbon capture, by converting natural gas to hydrogen and capturing the CO2. Emissions could be reduced by ~900,000 tonnes in the first phase due to industrial customers at Saltend Chemicals Plant switching to low-carbon Hydrogen. Triton Power's gas power plant will use fuel blended with Hydrogen ("£75 million bid win for Zero Carbon Humber's net zero ambition," 2021; "Zero Carbon Humber," 2021)

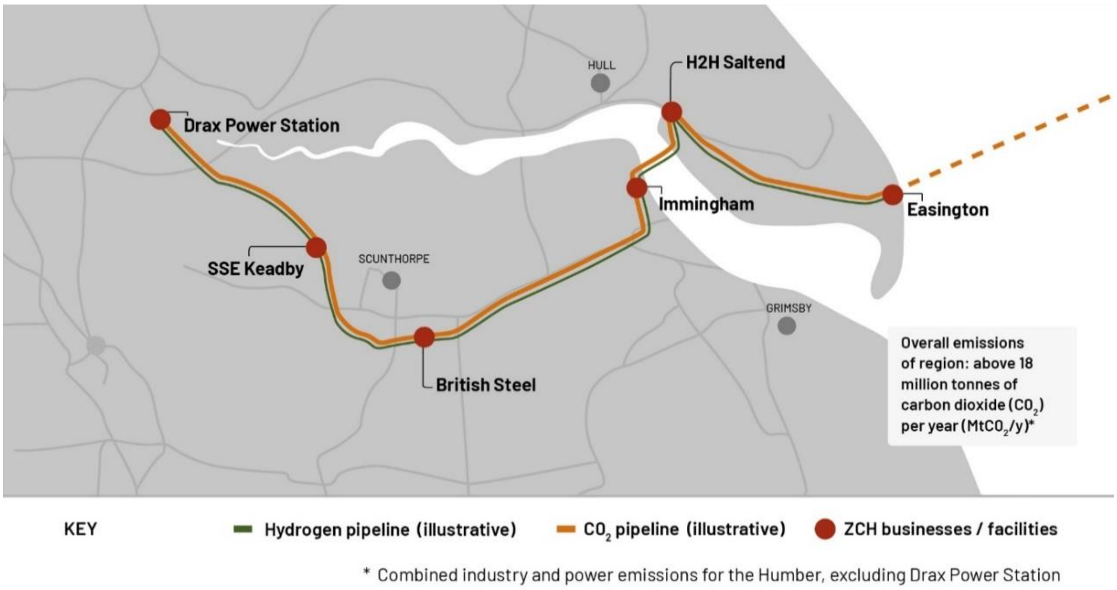

Figure 8 ZCH site map ("£75 million bid win for Zero Carbon Humber's net zero ambition," 2021)

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Uniper – Lindsey.firth@uniper.energy, tel. +44-7525-704146

vi. H2-Heat

Project Name	H2 Heat
Stakeholders and Partners	London South Bank University, Cadent, HiETA Technologies Ltd, Kelvion Searle, , Tata Steel (UK)
Expert Advisors	Ricardo Group,
Funding	EPSRC

Contact Email	Professor Y Ge, London South Bank University,
Website	https://gow.epsrc.ukri.org/NGBOViewGrant.aspx?GrantRef=EP/T022760/1 Starts:, 01 January 2021, Ends:, 31 December 2023, Value (£):, 995,241

The H2-Heat project aims to recover waste industrial heat for decarbonizing heat and cooling. A recent report estimates that of the 48 TWh/yr of industrial waste heat in the UK, 28 TWh/yr could be used for heating and cooling.

The project will develop long distance Hydrogen and Heat network, based on low-grade (210°C) and extra low-grade heat (~40°C) sources from a TATA steel plant. Metal Hydride (MH) heat-pumps will be used on-site along with a thermally driven chemical compressor.

The project will demonstrate a $5kW_{th}$ heating/cooling test system in the lab, to enable mathematical modelling of the system.

This is the first known project of its kind. Problems include the difficulty in choosing a thermal driven long-distance hydrogen and heat transport system; the associated MH alloys for space heating and cooling; and complicated designs of MH reactors in the H2-heat system. The project aims to solve these issues (EPSRC).

Also see Thermal energy transport for heating and cooling with innovative hydrogen (H2) technologies. EP/T022760/1. EPSRC funding award. Total value of project £979,291 (Oct. 2020-Sept. 2023). (REF https://www.lsbu.ac.uk/about-us/people/people-finder/prof-yunting-ge#id_third))

vii. HyDeploy

Project Name	HyDeploy
Stakeholders and Partners	Cadent, Northern Gas Networks, Keele University, HSE, ITM Power
Expert Advisors	Progressive Energy
Funding	ERDF and BEIS and Industrial Ofgem NIC and NIA funding
Contact Email	info@hydeploy.co.uk
Website	https://hydeploy.co.uk/

The HyDeploy project is hosted at Keele University and is a 3-stage programme. In the first stage this demonstrator project blends Hydrogen with Natural gas on a private network within the university. It is the first project in the UK to blend hydrogen with natural gas in a network. This phase was completed in Spring 2021.

The second and third stages will involve a larger demonstration in public networks in the North East and North West of England.

The second stage is due to start Spring 2021, with gas safety engineers visiting properties. More than 650 households in Winlaton are in scope with 90% engagement. The trial also includes a church, primary school, and several businesses. Winlaton was chosen because it is close to the Northern Gas Network site at Low Thornley.

In the HyDeploy project, Hydrogen is produced by electrolysers supplied by ITM Power ("Hydrogen is vital to tackling climate change,")

viii. H21

Project Name	H21
Stakeholders and Partners	Northern Gas Networks, Cadent, SGN, Wales & West Utilities, Health & Safety Laboratories, DNV GL, KIWA, amec foster wheeler, PSC, Kiwa Gastec, Cambridge Carbon Capture, Leeds Beckett University, ENA, iGEM
Expert Advisors	DNV, KIWA,
Funding	Various but mainly Ofgem NIC
Contact Email	h21@northerngas.co.uk
Website	https://www.h21.green/

H21 is a suite of gas industry projects ("H21 | Projects," n.d.) designed to support conversion of the UK gas networks to carry 100% hydrogen

The H21 project began in Leeds as a feasibility study ("H21 | H21 Leeds City Gate,"), examining whether converting the gas distribution network of a city (one of the same size and energy demand as Leeds) was both technically possible and economically viable. Led by Northern Gas Networks, the programme is focussed on conversion of the network to carry 100% hydrogen. This will aim to show that a hydrogen network is of no greater risk than the methane network heating our homes today (IChemE, n.d.).

The project website lists individual projects but for some of these there is no further information. A list of all the projects is given in Table 3. Where there is a lack of information, the summary description text for the project is shown.

Project Name	Notes
H21 NIC – Phase 1	See section H21 NIC (Network Innovation Competition) below

H21 NIC – Phase 2	See section H21 NIC (Network Innovation Competition) below
H21 Field Trials/Phase 2 Enabler	See section H21 Field Trials/Phase 2 Enabler NIA (Network Innovation Allowance) below
H21 Keighley and Spadeadam	See section H21 Keighley and Spadeadam below
NIA 269 – Industrial and Commercial Customers	Collating industrial and commercial data for NGN and Cadent networks to identify and understand mitigations required to convert industrial and commercial customers
NIA 268 Pre-Enabling Works for Phase 3, Occupied Trials	Preparing and enabling work for the first occupied 100% hydrogen trials which will form Phase 3 of H21
NIA 270 – Initial Hydrogen Supply Strategy	Exploring the effects of delivering hydrogen on the distribution network and planning mitigations and developing solutions to aid conversion
NIA 276 – Hydrogen Compatibility of Components	Researching the compatibility of materials with hydrogen, reviewing the current literature, and coordinating with the H100, Future LTS and HyDeploy projects
NIA 275 – Hydrogen Compatibility of Services	Reviewing the service connections from the distribution pipework to the ECV, including modelling the hydrogen demand for various pipe diameters and lengths.
H21 Social Science Research	See section H21 Social Science Research below
H21 North of England	See section H21 North of England below
H21 Strategic Modelling – Major Urban Centres	See section H21 Strategic Modelling – Major Urban Centres NIA (Network Innovation Allowance) below
H21 Domestic and Commercial Metering	See section H21 Domestic and Commercial Metering NIA (Network Innovation Allowance)H21 Strategic Modelling – Major Urban Centres NIA (Network Innovation Allowance) below
H21 Leeds City Gate	("H21 | H21 Leeds City Gate," p. 21)

Table 3 List of al H21 Projectl ("H21 | Projects,.)

H21 NIC (Network Innovation Competition)

The H21 NIC programme is in two phases as described below.

Phase 1

The first phase ("H21 | H21 NIC – Phase 1," 2020) has two components concerned with:

- changes to leakage levels in pipes, valves, joints, and fittings, using the Health and Safety Laboratories site in Buxton, Derbyshire.
- Ignition and combustion behaviour compared to natural gas, conducting trials at DNV-GL's research centre at Spadeadam in Cumbria

Phase 2

The second phase ("H21 Phase 2 Network Operations – NIC," n.d.) looks at whether or not the day to day procedures that we undertake on the gas network can still be undertaken safely in order to allow us to maintain a safe network. There are four parts to Phase 2:

- Operation and maintenance procedures
- Unoccupied network trials, using a section of network that is not currently in use
- Quantification of the comparative safety between natural gas and hydrogen. This work combines with the Hy4Heat project
- Communication with the public about 100% hydrogen conversion, to enable people to make an informed choice

H21 Field Trials/Phase 2 Enabler NIA (Network Innovation Allowance)

Field trials will follow on from H21 NIC phase 1 and 2.

H21 Keighley and Spadeadam

The primary focus of this project was to understand what was required at the NIC Phase 1a and 1b test sites

H21 Social Science Research

A detailed schedule of social science has been undertaken led by Leeds Beckett University focusing on the following: (info from https://www.h21.green/projects/h21-social-science-research)

- Baseline public perceptions of the safety of hydrogen and other energy technologies/vectors including how they vary by a range of socio-demographic and geographic variables.
- Insight into how people respond to the possibility of using 100% hydrogen in the three-key, gas-fueled social practices (heating, cooking, travelling), including how they vary by a range of socio-demographic and geographic variables
- Understand how public perception of the safety of hydrogen evolves across the range of socio-demographic and geographic variables when considering the H21 NIC evidence.
- Build a hydrogen research network of social scientists across the UK who may then become involved in the delivery of the proposed research activity or who may play advisory roles in the development of a body of research, data and expertise around the opportunities and challenges of hydrogen

H21 North of England

H21 North of England represents one scenario for hydrogen gas grid conversion, a credible engineering solution following completion of the last pieces of critical safety evidence, which will be provided by the Hy4Heat and H21 NIC programmes by 2023.

The project presents a conceptual design for converting the North of England to hydrogen between 2028 and 2035. The design incorporates a 12.15 GW hydrogen production facility, 8 TWh of inter-seasonal storage, all associated onshore infrastructure and the requirements of the associated carbon capture and storage scheme, scaling to 20 million tons per annum by 2035.

H21 North of England represents a credible first policy option for UK government.

H21 Strategic Modelling – Major Urban Centres NIA (Network Innovation Allowance)

Partners: NGN, Cadent, SGN, WWU

This project seeks to extend the principle of hydrogen conversion as established in the Leeds City Gate, across key UK urban centres.

The project focusses on three main questions:

1. Do the distribution networks have sufficient capacity to supply the required amounts of energy post conversion?
2. Can the large city networks be split into yearly sectors to allow for the conversion of part of a city during a summer period (the network is more flexible at this time due to reduced demand and the impact on customers is reduced due to a lowered requirement for heating) whilst leaving a network robust enough to maintain supply to converted and non-converted areas for the following winter?
3. Can the yearly sector be split into approximately 26 zones to allow for smaller areas to be converted within a week thereby reducing the disruption and loss of gas supply to customer to a practicable minimum?

Report H21 – Mapping the demand of hydrogen conversion areas: https://www.h21.green/wp-content/uploads/2018/01/30803-NGN-Hydrogen-Conversion-areas-mappingFinal.pdf

H21 Strategic Modelling Major Urban Centres Final Report https://www.h21.green/wp-content/uploads/2018/11/H21-Strategic-Modelling-Major-Urban-Centres-report-final-V1.pdf

H21 Domestic and Commercial Metering NIA (Network Innovation Allowance)

This project will determine the suitability of existing domestic and commercial meters for operation on a hydrogen network.

Split into three phases, the scope of the project will involve an initial review of hydrogen meter technologies and applications world-wide.

After the design of the metering test facility is finalised the data will be collated into a final report.

Phase 1 report https://www.h21.green/wp-content/uploads/2018/11/H21-Consumer-and-gas-network-metering-phase-1-report.pdf

ix. Hy4Heat

Project Name	Hy4Heat
Stakeholders and Partners	Department for Business, Energy & Industrial Strategy, Kiwa Gastec, Progressive Energy, Embers and Yo Energy and other industry organisations and gas equipment companies.
Expert Advisors	ARUP
Funding	Department for Business, Energy & Industrial Strategy
Contact Email	hy4heat@arup.com
Website	https://www.hy4heat.info/

Hy4Heat is a programme commissioned by the Department for Business, Energy & Industrial Strategy (BEIS) to explore whether replacing natural gas (methane) with hydrogen for domestic heating and cooking is feasible, and could be part of a plausible potential pathway to help meet heat decarbonisation targets.

To do this the programme will seek to provide the technical, performance, usability and safety evidence to demonstrate whether hydrogen can be used for heat and cooking in buildings.

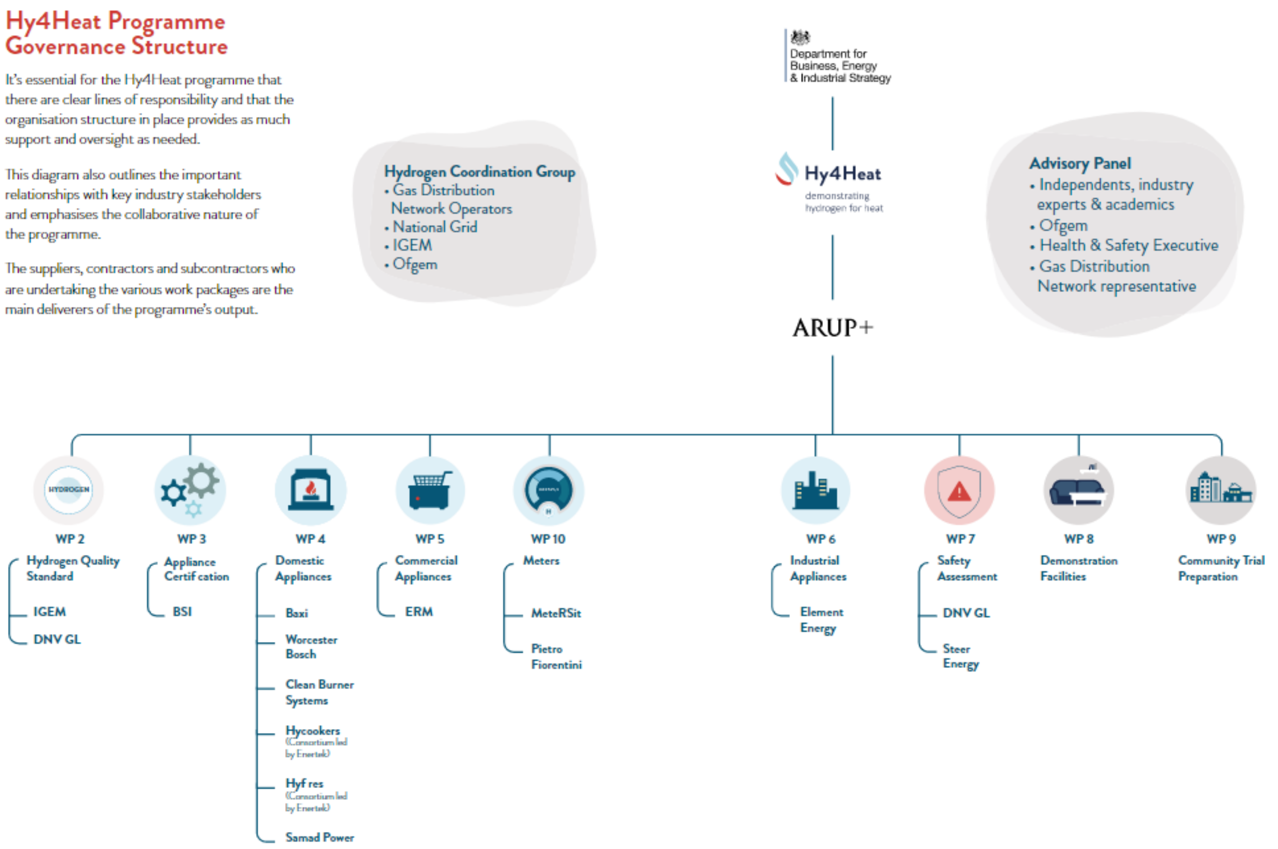

Figure 9 Hy4Heat work programmes and partner leads

x. UK Hydrogen Corridor

Project Name	UK Hydrogen Corridor
Stakeholders and Partners	University of Leeds, Tees Valley and Leeds City Regions
Expert Advisors	TWI
Funding	UKRI Strength in Places Fund
Contact Email	A.J.Pimm@leeds.ac.uk
Website	https://www.leeds.ac.uk/downloads/download/750/establishing_the_uk_hydrogen_corridor_reports

The University of Leeds is part of the 'Establishing the UK Hydrogen Corridor' Strength in Places Fund project which brings together leading researchers and key stakeholders from industry and government. Together, we will develop the knowledge and skills to support the role of hydrogen in decarbonising heat, transport and industry in the Tees Valley and Leeds City Regions.

The project is led by TWI Ltd which was awarded seed corn funding in 2019 and has since submitted a full proposal to the fund (Ward,)

Reports in the website: Establishing_the_UK_Hydrogen_Corridor - Hydrogen Technology State of the Art, Establishing the UK Hydrogen Corridor - Hydrogen applications in transport, Establishing the UK Hydrogen Corridor – socio-economic, environmental & regulatory issues (Andrew J. Pimm et al., 2019; Cameron Rout et al., 2019; James Van Alstine and Claire Bastin, 2019)

xi. National Grid Hydrogen Test Facility

Project Name	National Grid Hydrogen Test Facility
Stakeholders and Partners	National Grid, Northern Gas Networks (NGN), Fluxys Belgium, DNV GL
Expert Advisors	HSE
Funding	NIC and NIA funding
Contact	Surinder Sian, Senior Corporate Communications Manager, +44 (0)7812 485 153, surinder.sian@nationalgrid.com

Website	https://www.nationalgrid.com/5-aug-2020-national-grid-launch-ps10m-trial-project-test-if-hydrogen-can-heat-homes-and-industry

This £10m project will deliver a hydrogen test facility at DNV GL's site in Spadeadam, Cumbria. Hydrogen blends up to 100% can be tested on a range of decommissioned assets. The facility will be used in H21 phase 2. ("National Grid to launch £10m trial project to test if hydrogen can heat homes and industry | National Grid Group," 2020)

xii. H100 Fife and H100 Feasibility and FEED Study

Project Name	H100
Stakeholders and Partners	SGN, Cadent, Norther Gas Networks, Wales and West Utilities, Baxi, Bosch, HyCookers, HyFires, Scottish Government, Offshore Renewable Energy, Catapult, Scottish Enterprise, Fife Council, Scottish Power Energy Networks, Scottish Water, HSE Science Division, , Environmental Resources Management, National Grid, GTC, Energy Utilities Alliance, Energy Skills Partnership, Diageo, Scottish Hydrogen Fuel Cell Association, Hy4Heat, National Physics Laboratory, University of Edinburgh and Enertek International Ltd
Expert Advisors	Kiwa, Arup, DNV-GL
Funding	Various but mainly Ofgem NIC
Contact Email	n/a
Website	https://info-h100fife.co.uk/

A network innovation competition was announced in 2020 to deliver a 'first of a kind' 100% hydrogen demonstration, using hydrogen to decarbonise heat, using the gas network. This project commenced on 1st April 2021 with a completion date of 31st March 2027.

This project involves using the energy generated by offshore wind to power electrolysis to form green hydrogen, which can then be stored and transported through the current gas network. This will initially feed an on-site H_2 facility, but eventually will provide zero carbon heating for 300 homes in the local area.

The innovation is being led by SGN ("Gas NIC Submission," 2020; "H100 Fife | Future of Gas | SGN,".; "Project Direction: H100 Fife – SGN | Ofgem,") Construction will begin in Q4 2021, with the operational phase commencing in Q4 2022.

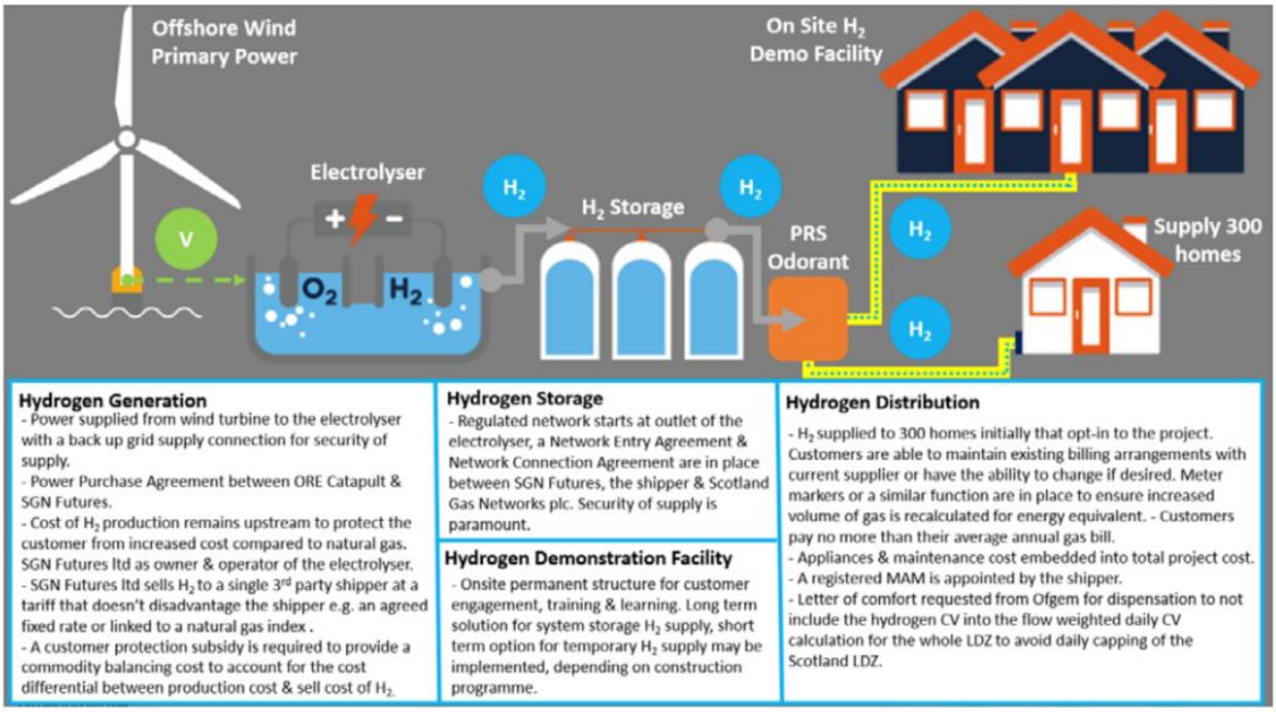

Figure 10 H100 project concept

A collection of studies completed by SGN which highlight the capacity and challenges of converting parts of the gas network in the north east of Scotland to hydrogen. The H100 Feasibility and FEED study was conducted in partnership with Costain (Aberdeen), ARUP (Levenmouth) and Wood (Macrihanish). This study is to give an indication and estimation of design costs in converting these areas to 100% hydrogen. The reason for choosing these areas is suggested to be the capacity to upscale to the UK ("H100 NIA: Feasibility and FEED Studies | SGN Your gas. Our network.,".)

The study covers two workstreams, one focussed on evidence and safety and the other on feasibility and front-end engineering and design (FEED).

xiii. Acorn

Project Name	Acorn
Stakeholders and Partners	Pale Blue Dot Energy, SSE, Petrofac NECCUS, LNG9/GB-Tron, Strathclyde University Centre for Energy Policy and National Grid
Expert Advisors	Pale Blue Dot Energy,
Funding	Department for Business, Energy & Industrial Strategy
Contact Email	info@pale-blu.com
Website	https://pale-blu.com/acorn/

The largest single hydrogen project in the Aberdeen region is the Acorn project led by Pale Blue Dot Energy. The Acorn project involves CCUS fitting the St Fergus power station to allow sequestration into the Acorn storage site in the North Sea using the pre-existing Goldeneye, Atlantic and Miller pipelines. Currently over a third of all natural gas in the UK arrives onshore at the St Fergus site. As such there are plans to build a methane reformation facility on the power plant site to generate hydrogen by 2025. The produced hydrogen can be blended with the natural gas, initially with 2% replacement, but up to 20% replacement in time. This can then be piped around the UK to reduce carbon footprints of heating and energy intensive industry. This is to be combined with several other projects in an effort to bring a pipeline of hydrogen directly to Aberdeen, with the cities grid eventually being 100% hydrogen. (“Acorn CCS,”; Element Energy, 2020)

The Acorn project is led by Pale Blue Dot Energy, but also comprises a host of partners including SSE, Petrofac NECCUS, LNG9/GB-Tron, Strathclyde University Centre for Energy Policy and the National Grid.

A range of associated initiatives in line with Acorn were promised £30m funding from the British Government in March 2021 as part of the Industrial Strategy Fund. These initiatives cover:

- The detailed engineering required to move the Acorn CCS and Hydrogen projects to a final investment decision
- Developing a new CCS-equipped power station at Peterhead which would become an early customer for the Acorn infrastructure
- An assessment of the potential to re-use onshore pipelines to transport CO_2 from the central belt of Scotland to the Acorn Project
- An engineering design programme for a carbon capture system on a gas-fired power station in Grangemouth
- Development of a “fabrication yard ready” design of a new class of ship which can service the needs of coastal CO_2 emitters around the UK for delivery at Peterhead port

- *Figure 11 Acron project location*

Other Projects

xiv. HECTOR

Hydrogen Waste Collection Vehicles in North West Europe (HECTOR) has deployed a hydrogen waste vehicle in Aberdeen as part of a pilot study. The study is to test operating conditions and act as a base case for further roll out.

xv. H2 Aberdeen

An initiative run by Aberdeen City Council with the aim of bringing a hydrogen economy to the city off the back of the 2015 Aberdeen Hydrogen Strategy, a document published in the aftermath of the oil crash of late 2014. The aim of H2 Aberdeen is to encourage growth in hydrogen energy, both blue and green. H2 Aberdeen has formed the backbone of many of the projects mentioned in this list ("H2 Aberdeen | Aberdeen City Council," 2021)

xvi. Hydrogen Bus Project

An EU funded incentive, which delivered hydrogen buses in Jan 2020 and double decker buses in Jan 2021. The Aberdeen Hydrogen Bus Project was set up by Aberdeen City Council, the Scottish Government and the EU comprised £8.3m funding to roll out a series of hydrogen powered buses in the city. Stakeholders in the project were also Hy Transit, Innovate UK, First Bus, Scottish Gas Network, BOC, Scottish and Southern Electricity and Scottish Enterprise, with First Bus running the bus services.

The double decker busses first introduced in Jan 2021 are believed to save up to 1kg of CO_2 for every 1km travelled and represent approximately £0.5m investment per vehicle. These buses represent the outcome of the JIVE project, a pan-European initiative led by Madrid, but also featuring London and Birmingham in the UK as well as Aberdeen. ("The Aberdeen Hydrogen Bus Project,")

Completed Projects

xvii. Kittybrewster + Aberdeen City Hydrogen Energy Storage

Kittybrewster became the UK's first hydrogen refilling station when it opened in 2015, and was followed after by the Aberdeen City Hydrogen Energy Storage Project (ACHES) launched in 2017. The project was part of an initiative led by BOC with partners of Aberdeen City Council, Toyota and Hyundai. As part of this project the council bought 18 Toyota Mirai hydrogen vehicles for their fleet. This project allowed for the developments more recently of the hydrogen buses scheme mentioned above.

As part of this project the city council has adopted further hydrogen vehicles such as cars, trucks, road sweepers and waste vehicles, which could be refuelled at either Kittybrewster or ACHES.

xviii. HyTrEc

Hydrogen Transport Economy (HyTrEc) for the north sea region was a project run by the EU from 2014-2020 where partners from the UK, Germany, Sweden, The Netherlands and Norway worked together to support the introduction of hydrogen transport into regions most reliant on the North Sea oil and gas infrastructure. Other partners on the UK side of this project were Aberdeen City Council and Pale Blue Dot. This project helped deliver the aforementioned ACHES facility along with helping to develop the hydrogen supply chain ("HyTrEc Interreg VB North Sea Region Programme,")

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Chapter 4 Project Reference Table

Project name	Purpose	Funder	Year/s	Partners	Heat recovery	Web Link
ZCH/H_2H	Hydrogen generation; CCS; hydrogen pipeline; carbon pipeline	Industrial Strategy Challenge Fund (Phase 2)	Funding Approved March 2010	Equinor, British Steel, Drax, National Grid, px Group, SSE, Uniper.	No	https://www.zerocarbonhumber.co.uk/
H21 Phase 1	Assess safety of transporting 100% hydrogen in gas network	Ofgem NIC	Jan 2018 -	Northern Gas Networks, Cadent, SGN, Wales & West Utilities, Health & Safety Laboratories, DNV GL, KIWA, Amec Foster Wheeler, PSC, Kiwa Gastec, Cambridge Carbon Capture, Leeds Beckett University	No	https://www.h21.green/
H21 Phase 2	Assess safety of transporting 100% hydrogen in gas network	Ofgem NIC	Jan 2020 -	(as above)	No	https://www.h21.green/
Hy4Heat	Product Demonstration	BEIS	due to complete by 2020/21	Equinor, Northern Gas Networks	No	https://www.hy4heat.info/
UK Hydrogen Corridor	Research Demonstration	Strength in Places Fund	Seed corn funding awarded 2019. Full funding bid submitted	TWI Ltd, University of Leeds	No	http://www.leeds.ac.uk/info/130564/energy/767/hydrogen

Project name	Purpose	Funder	Year/s	Partners	Heat recovery	Web Link
H2-Heat		EPSRC	Jan 2021 - Dec 2023	HiETA Technologies Ltd, Kelvion Searle, Ricardo Group, Tata Steel (UK)	Yes	https://gow.epsrc.ukri.org/NGBOViewGrant.aspx?GrantRef=EP/T022760/1 https://gtr.ukri.org/projects?ref=EP%2FT022760%2F1
Humber Zero	Industrial Decarbonisation	Innovate UK's Industrial Strategy Challenge Fund	Ongoing since 2018	Humber Industrial Cluster Plan (Humber Refinery Phillips 66, Uniper, VPI-Immingham, Immingham Port, North Humber Industry and Docks, Easington Gas Terminal, other industry, Gas Network, Off shore wind farm, Saline Aquifer Experts: Wood Group, Imperial College, London and the University of Sheffield	Yes	https://www.humberzero.co.uk/
Green Hydrogen for Humberside	Feasibility and scoping study for deploying green hydrogen	Innovate UK's Industrial Strategy Challenge Fund	2020	ITM, Element Energy	Not mentioned	https://www.itm-power.com/news/green-hydrogen-for-humberside-project-deployment-study

Project name	Purpose	Funder	Year/s	Partners	Heat recovery	Web Link
HyDeploy Phase 1	H_2 injection into NG supply on a university campus	Ofgem's Gas Network Innovation Competition, Cadent Gas Ltd, Northern Gas Networks	Oct 2019-Spring 2021	Keele University, Cadent and Northern Gas Networks, Health and Safety Executive (HSE)	No	https://hydeploy.co.uk/
HyDeploy Phase 2 & 3	H_2 blending in public networks	NIA, NIC and BEIS	Early 2020 onwards	(as above)	No	https://hydeploy.co.uk/
National Grid Hydrogen Test Facility	Hydrogen Test Facility (on decommissioned assets)	NIC	start construction in 2021 with testing beginning in 2022	National Grid, Northern Gas Networks (NGN), Fluxys Belgium, DNV GL. Surinder Sian, Senior Corporate Communications Manager, +44 (0)7812 485 153, surinder.sian@nationalgrid.com		https://www.nationalgrid.com/5-aug-2020-national-grid-launch-ps10m-trial-project-test-if-hydrogen-can-heat-homes-and-industry

5. Conclusion

This study provides an overview of hydrogen within energy systems, an outline of UK lighthouse projects and techno-economics of heat recovery from hydrogen production clusters. After an introductory section on current perspectives of hydrogen within future energy systems in the first chapter, existing UK literature were explored to provide standardised thermal demands in UK homes with a list of 5 publicly available heat map platforms aimed at assisting district energy master-planning and feasibility studies (Chapter4).

A notably wide range exists on standardised UK domestic thermal demand from empirical observations that rage 86 kWh/m^2/year to 201 kWh/m^2/year. A total of 19 UK-based Hydrogen demonstrators were outlined in chapter 5 amongst which only one demonstrator aims to generate evidence on simultaneous H_2 production and district heating with the primary fuel being excess heat from steel production. Given that the overall ambition of this work has been to examine scientific literature on the feasibility of heat recovery from H_2 production facilities, the early findings that have emerged from this review are as follows:

1. Most of Hydrogen-related scientific literature encountered in the course of compiling this work focused on the improvement and characterisation of fuel cell stacks, improving operational efficiency of FC and electrolysers, identification of new (and less expensive) cathode and anode material, improvement of hydrogeneration time, starting materials and solvents in electrolysers. At system level, hydrogen research is focused on improving round trip efficiencies of production, storage and burning of Hydrogen, and economic H_2 production at scale. The issue of recovery of heat from the electrolysis process – which remains a whole system level challenge – was scarcely addressed in scientific literature. It is only in the past few years that a small number of scientific literature have begun to cover the subject of heat recovery from a FC facility and such small and case-specific studies hinder conclusive remarks on broadly agreed optimal system designs and specification. In the absence of a particular H_2 production technology, substantial uncertainty remains on the feasibility of heat recovery from H_2 production clusters and the impact on overall process efficiencies (see 2).
2. The recovery of heat from a Hydrogen electrolyser facility will have to address the great diversity of FC designs, operating temperatures (from 100 to 1000°C) and layouts that are available. For instance, 72 different system layouts were suggested in one examination of Solid Oxide FC plants alone (although of this 11 were selected as the most practical). This indicates that a heat recovery solution from a H_2 production facility remains specific to the project and plant types. Additionally, overall hydrogen production is more efficient at higher temperatures, therefore extracting heat from an H_2 production facility cools the process and has implications for the overall process efficiency.
3. There is a range of scientific material that examines the production of hydrogen with the original fuel being (typically a high temperature) heat source. The overall process efficiency is then improved by recovering some of the low-grade heat for other processes. The results of these studies however cannot offer guidance on recovering heat from an electrolysis plant where the original fuel is electricity.
4. Biomass derived hydrogen is undertaken at either high (700-1400°C for gasification/reforming) or low temperatures (30-100°C for microbial and low temperature electrochemical process). Recovery of heat from either process has overall efficiency implications with scarcely any coverage of heat recovery from such a process.
5. The profile spread and magnitude of a community's thermal demand offer a limited view of future horizons as fuel switching to low carbon sources have been found to result in drastic changes in post-retrofit characteristics of thermal demand.

A successful design for the recovery of low /medium grade heat from a hydrogen production facility therefore remains extremely project-specific, and its overall engineering merits are heavily impacted by the fuel that maintains H_2 production process (i.e. waste heat or electricity), the process type (electrolysis, biomass-derived H_2, etc.), plant scale and the thermal network design for the delivery of excess heat.

Appendix 1: Version Control Record

Version	Change details and reason for new version	Latest date	Owner
A	Draft Report issued to JH Ramboll	10/05/2021	MR
B	Final formatted version issued to JH at Ramboll	12/05/2021	LB

Further information on the dynamics of heat recovery from electrolysis systems:

1. Electrolyser Heat Recovery and Efficiency:
   This aspect also needs to be answered for the electrolysers which are widely used currently (PEM and alkaline electrolysers). In the report it is mentioned that recovering heat will reduce the efficiency. While this may be true for the technologies which are currently under development it is not exactly applicable for the green hydrogen projects which are under development. On the other hand recovering waste heat will increase the overall efficiency of the project.

This statement is correct in that removing heat from some of the hydrogen production processes has efficiency implications. Remember that the original scope of the work that we undertook was to look at all H2 production processes, so for instance if the process is thermolysis using nuclear waste heat, then extracting heat from the process will impact the H2 production efficiency and the degree of overall efficiency (η) that is sought is the big question (which is determined by whether the system design wants to prioritise H2 production over waste heat at all costs, or if it wants to allow both H2 and heat to be derived). For PEM see 2.

2. Electrolyser Waste Quantity and Temp:
   It would be good indicate what the literature says about the waste heat availability (in terms of % of input energy) and temperature of waste heat. Where these 2 parameters stand now and how these parameters are likely to change as the electrolyser technology evolves. Again we are mainly interested in the PEM and alkaline electrolysers which are likely to be the main electrolyser types for the short term future and solid oxide electrolysers which may be available in long term future.

Waste heat management still remains a 'live' science problem as so far the scientific community has been concerned with improvement of [i] catalysts / starting material / solvents / inner cell design [ii] timing of dehydrogenation [iii] round trip efficiency [iv] integration of H2 into gas networks [v] production of H2 at scale. Therefore, we emphasise again that there is little scientific material available on heat recovery from electrolysers.

Importantly when a scientific report talks about waste heat management, it often does not refer to the overall impact of this (in the form of % reduction in η). An example for PEM is that up to 30 of the nominal power input into a PEM cell can be recovered in the form of heat (see highlighted section Doc 1, p2). But no mention of the impact on H2 production (this literature only states that overall cell efficiency remains at 70% while heat is recovered from the cell with a 63°C -70°C inlet/outlet temperature management. Note electrolyser efficiency is the efficiency with which the electrolyser converts electricity into hydrogen).

What is even more important to emphasise here is that the literature often reports on PEM and Alkaline electrolyser rigs that are small scale laboratory equipment. As the size of electrolysers increase towards industrial scale (which is what is needed for DH applications), the design of the cells begins to change the H2 production and heat availability (see highlighted section Doc 1, p3). Therefore, heat recovery reports on lab-based units can be taken as an indication of the behaviour of an industrial scale electrolyser.

A thesis submitted to Delf university states that theoretically it is possible to recover up to 92% of waste heat from PEM electrolysers and that it makes PEM electrolysers 14% more efficient (see Doc 5, p32). I think it is quite high as generally heat recovery efficiencies on water-to-water systems is around 60-80%. Another similar note is that heat recovery from PEMs can make the overall system efficiency improved by 15% (see Doc 3, line 126).

Another investigation of a 5kg / hr H_2 PEM electrolyser states that 85% of heat from PEM stack is recoverable at a temperature of 75°C without effecting the H2 production (see Doc 3, line 210). Electrolyser efficiency in this model is 63%, heat recovery efficiency is 31.6% and therefore overall efficiency is 94.6% (see Doc 3, line 217). This document states that these values can be scaled up to any PEM size (see Doc 3, section 6.4). This as you can see is slightly different with Doc 1, P3 (section highlighted under 'improved cell and stack design') that states when moving towards industrial scale PEMs, cell area is relatively increased (which indicates the fluid will have a greater chance for heat recovery). So if anything both literature seem to agree that opportunities for heat recovery improves as the scale of PEM system increases.

Recall from the original report submitted to Ramboll that there are applications whereby the removal of heat from H2 generation reduces hydrogen production (mostly where input fuel is excess heat and the process involves reforming hydrocarbons), whereas in PEM applications removing excess heat can improve the overall efficiency primarily as it helps the gases that are leaving the electrolyser stacks to be much cooler and therefore easier to compress or liquify. Again, this shows how case-specific, size-specific and technology specific these efficiencies are.

I did not find any literature that covered waste heat topic from Alkaline electrolysers.

3. Utilisation of Waste Heat for District Heating:
   As we agree this needs to be assessed from case to case basis and the question needs to be addressed from H2 project developer's point of view and District Heating Network Operator's point of view. For H2 project developer it is likely to reduce the auxiliary power consumption and generate additional revenue stream, and hence the developers may be interested in the opportunity irrespective of the scale. For DHN operators it may depend on what counterfactual they have got, electrolyser waste heat may not be an attractive option if they have cheap and low carbon waste heat options (such as EFW) but if we are comparing against some other waste heat sources such as sewer waste heat or river source waste heat then the electrolyser waste heat may be an attractive option. We totally agree that for DHN operators there is a lot more chance that the waste heat recovery will be financially viable at large scale and at closer proximity from the waste heat source. It will be good to indicate what literature says about this.

The most interesting and up to date figure I could find on this was a piece of research that is not even yet published by a group in Durham University. They have identified literature that reports that up to 40% of input energy into PEM electrolysers are vented into the atmosphere as waste heat (see Doc 3, line 90). They also outline opportunities for recover heat from both PEM stack as well as the hot O2 and H2 gases that leaves the system to be fed into a DH system. The excess heat recovered from PEM process can be delivered at 45-75°C (so suitable for 4th and 5th generation DHS). Again based on this model (outlined in Doc 3) an improvement of 31.6% is gained as a result of heat recovery from PEM stack and output hot gases that when added to an H2 production efficiency of 63% (this is the electrolyser efficiency), an overall efficiency is 94.6% is achieved.

Doc 3 goes on to do an economic calculation based on a waste heat from PEM value of £27.62/MWh (see Doc 3, line 423).

4. Blue Hydrogen Waste Heat:
   The literature review has indicated the option of recovering waste heat from compressors. Is there any indication in the literature about recovering the low-grade waste heat from blue hydrogen production itself (e.g waste heat from steam methane reformation)?

Again the most relevant literature that I could source was Doc 3. This document states that a 1 MW combined Hydrogen and Heat cluster (CHH) using PEM technology that is operated 5 hours per day on cheap renewable electricity can generate enough heat for a small DHN that supplies 20 homes. If CHH was operated on a 24hr basis it would be able to supply 96 homes (see table 4). Table 5 also shows what size CHH is required for different size DHN.

So far as steam methane reforming (SMR) is concerned, it is important to note that it is an overall endothermic process (i.e. you have to put heat in to initiate and maintain the process). So again this leads you into a system design that can be either optimised for H2 production or both H2 and low grade heat production. Interestingly in the first stage of SMR heat is put in (equation 1) and in the second stage of SMR heat is released (equation 2), but the literature that I came across mostly concentrated on recovering heat from process 2 and putting in back into process 1, rather than redirecting it as an input into DH systems.

1st stage of SMR $CH4g+H2Og \rightarrow COg+3H2g$ $(\Delta H=206kJmol-1)$

2nd stage of SMR $CO_g + H_2O_g \rightarrow CO_{2g} + H_{2g}$ ($\Delta H = -41 kJmol^{-1}$)

See Doc 2 as a typical treatment of reusing heat from second stage to improve overall efficiency. Most importantly since temperatures concerned in SMR are quite high (800 – 1200°C), this high exergy temperatures are mostly recuperated to do thermo-chemical works (useful works) rather than feeding DH networks. This however does not exclude DH as an option for improving SMR, but rather than the focus of science has been to utilise high temperatures in SMR for high quality thermo-chemical work.

The following Documents were also provided with the Literature Review Supplementary Information:

Doc 1: ‘A Modular Design Approach for PEM Electrolyser Systems with Homogeneous Operation Conditions and Highly Efficient Heat Management’ (F.J. Wirkert, J. Roth, S. Jagalski, P. Neuhaus, U. Rost, M. Brodmann). International Journal of Hydrogen Energy, 45 (2020), 1226 – 1235.

Doc 2: ‘Exergy Analysis of Waste Heat Recovery Section in Steam-Natural Gas Reforming Process’ (M.H. Shariati and F. Farhadi). Energy Fuels, 29 (2015), 3322 – 3327.

Doc 3: ‘A Combined Heat and Green Hydrogen (CHH) Generator Integrated with a Heat Network’ (D. Burrin, S. Roy, A.P. Roskilly, A. Smallbone). [*Subsequently published in Energy Conservation and Management, 246 (2021), 114686*].

Doc 4: ‘Hydrogen – A Sustainable Energy Carrier’ (K.T. Moller, T.R. Jensen, E. Akiba, H. Li). Progress in Natural Science: Materials International, 27 (2017), 34 – 40.

Doc 5: ‘Heat Management of PEM Electrolysis: A Study on the Potential of Excess Heat from Medium- to Large-Scale PEM Electrolysis and the Performance Analysis of a Dedicated Cooling System’ (W.J. Tiktak, October 2019).

APPENDIX B: WORKSHOP / WEBINAR SUMMARIES

The following Summaries are provided:

- Technical Workshop 1 (29/06/2021).
- Technical Workshop 2 (03/08/2021).
- Final Webinar (28/09/2021).

Technical Workshop 1 (29/06/2021)

SYNERGY STUDY
HEAT RECOVERY FROM HYDROGEN PRODUCTION

Workshop 1

Tuesday 29 June, 2021

RAMBOLL Bright ideas. Sustainable change.

EMBASSY OF DENMARK
London

AGENDA

01 Introduction / Study Background

02 Synergy Study Project Team

03 Presentation by Danish Energy Agency

04 Study Objectives

05 Technical Overview

06 Study Status and Initial Findings

07 Next Steps and Workshop 2

INTRODUCTION
STUDY BACKGROUND

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STUDY BACKGROUND

POTENTIAL ROLE AND SCALE OF HYDROGEN AND WASTE HEAT (UK PERSPECTIVE)

- Ramboll Energy was appointed by the Danish Energy Agency to undertake the Synergy Study between Hydrogen production and Heat Networks.
- Noting the UK Government's 2050 Net Zero target, there is an increasing focus on Hydrogen to provide a credible option for decarbonising the UK energy system.
- Where Hydrogen is produced, an amount of waste Heat is also generated. This presents an opportunity for the District Energy sector to capitalise on what otherwise would be vented to the atmosphere.
- UK has been targeted due to ambitions timescale for Hydrogen development and deployment.
- Building on a previous 2020 Study, Ramboll Energy identified that Hydrogen production could reach 250 TWh and up to 569 TWh by 2050, resulting in waste Heat of 22 TWh and up to 50 TWh.
- The UK Clean Growth Strategy (2017) estimates that 17% of the UK Heat demand will be delivered through DH by 2050 which would account to 32 TWh of heat.
- Waste heat from Hydrogen could potentially meet 70% and over 150% of currently estimated DH Demand by 2050 hence there is definitely a market to be investigated.

SYNERGY STUDY
PROJECT TEAM

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SYNERGY STUDY PROJECT TEAM

Jacob Byskov Kristensen
Energy Policy Advisor

Jen Hearne
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Emily Agus
Deputy Project Manager

Amey Karnik
Hydrogen

Dan King
Hydrogen

Aimilios Spinoulas
Heat

Ana Gonzalez Vega
Heat

William David MacRae
Heat/Hydrogen

RAMBØLL

PRESENTATION BY
DANISH ENERGY AGENCY

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HEAT RECOVERY FROM HYDROGEN – UK STUDY

OVERVIEW AND INTRODUCTION TO TECHNICAL WORKSHOP

Energy Policy Advisor, Jacob Byskov Kristensen – June 2021

CONTENT

- Introduction to program
  - Who, Why, What
- Background and motivation for UK study
  - Heat decarbonisation debate in the UK
  - General technical overview/concept
  - Danish study of relation between hydrogen and district heating
  - Case examples

WHO ARE WE?

Energy Governance Partnership

- Government to government-program funded by the Danish Government
- Part of the Danish Governments Global Climate strategy.
- Provide inspiration and support for heat decarbonisation policy in UK and Scotland.
- Situated at the Danish Embassy in London, coordinated and supported by experts and resources in the Danish Energy Agency.

MINISTRY OF FOREIGN AFFAIRS OF DENMARK
The Trade Council

Danish Energy Agency

Jacob Byskov Kristensen, Energy Policy Advisor

- Danish Embassy in London
- Leading on district heating
- Former Danish Energy Agency, district heating office

WHY HAVE SUCH A PROGRAM?

- Part of Danish Governments *Global Climate Action Strategy.* Similar programs in [18] countries (>70% of global emissions)
- Mission: Speed up the global green energy transition by making Danish expertise and experience easily available - where it is wanted
- …while at the same time maturing markets of key interest to Danish companies

…IN THE UK?

- UK have an ambitious climate agenda, but struggles to transform the heat and building sector – something Denmark has a lot of experience and success doing
- A big (potential) market for low-carbon heating solutions

WHAT

Program activities – examples

- Main tool: Close relation and on-demand knowledge-sharing with public officials in Scotland and UK
- Study tours for elected and public officials
- Written evidence for legislative and policy processes incl. public consultations
- Participation in working groups
- Facilitating and financing; conferences, studies, translation of documents etc.

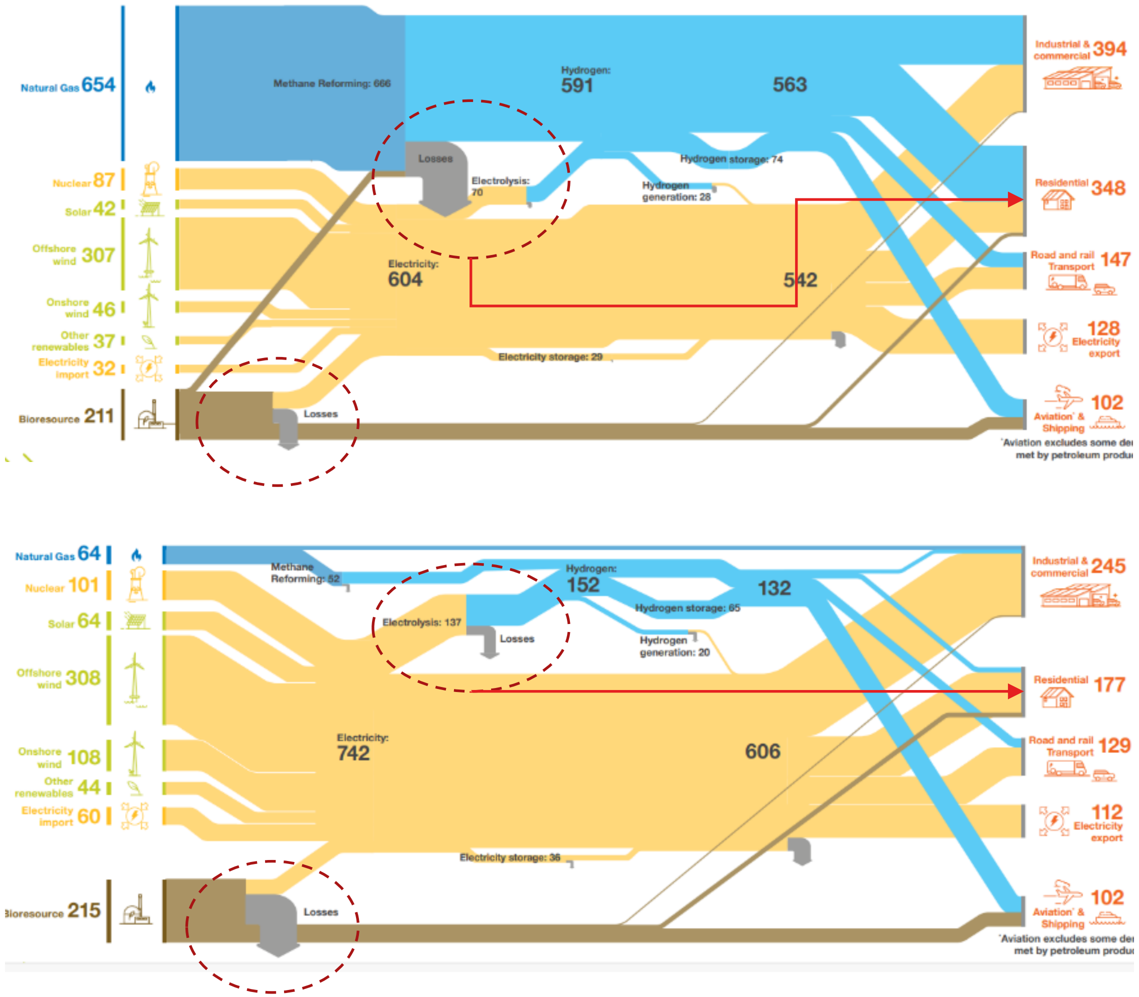
BACKGROUND AND MOTIVATION

FOR STUDY ON HEAT RECOVERY FROM HYDROGEN IN UK

WHY THIS STUDY – FROM US?

- The UK heat decarbonisation debate
  - Electrification or hydrogen absorbs attention
  - Hydrogen will have important role – one way or another
- Expected knowledge gaps and/or policy barriers
  - Heat recovery form hydrogen is “new” – heat recovery from industry isn’t
- Politically opportune
  - Synergetic link to H2 would help both sides and could move HN up the political agenda
  - Unleashing (possible) synergies would be closely linked to zoning
- The Danish case could be valuable
  - Great political, economic and scientific focus atm
  - DH attracting PtX investments: Can recuperate costs, increase H2 production & provide valuable green profile

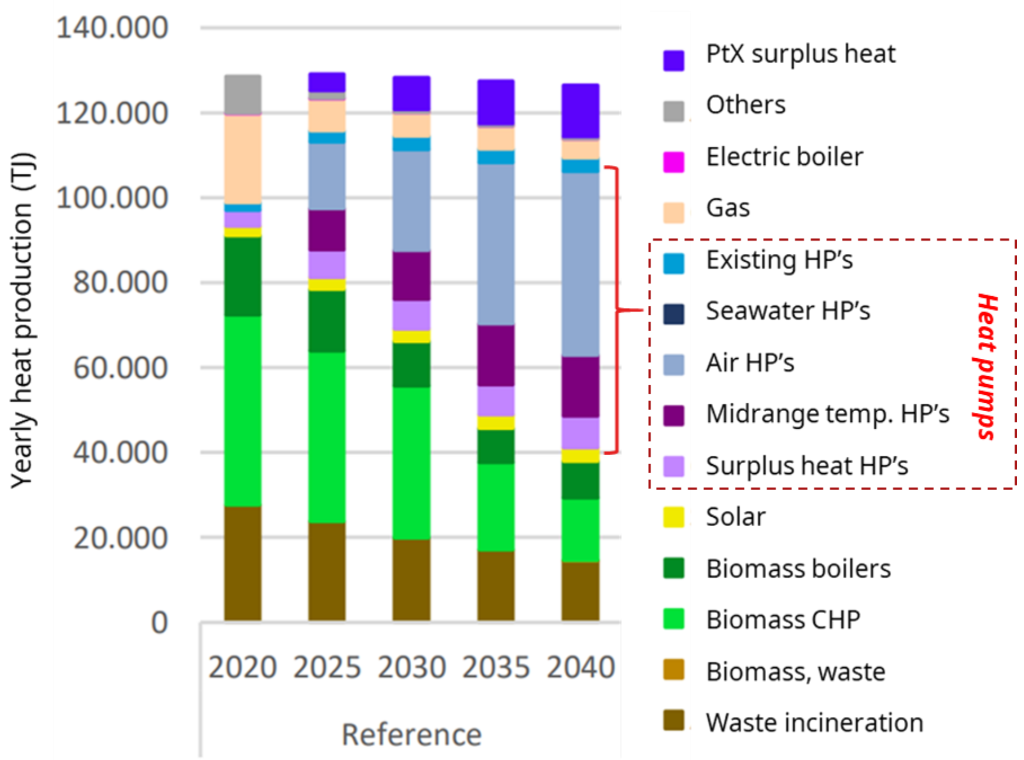
Examples from National Grid energy system scenarios (2020)



HYDROGEN AND DISTRICT HEATING IN DENMARK

- Hydrogen = PtX in Danish debate
- PtX strategy expected this summer/autumn
- Main PtX funding stream through EU IPCEI process
- DH has caught a big interest in hydrogen/PtX
  - Currently heating >68% of households
  - So far decarbonisation heavily based on biomass
  - Heat recovery from PtX shows great potential
  - Danish Government: *"Danish PtX strategy will be linked closely with district heating"*

Forecasting production of district heating in Denmark



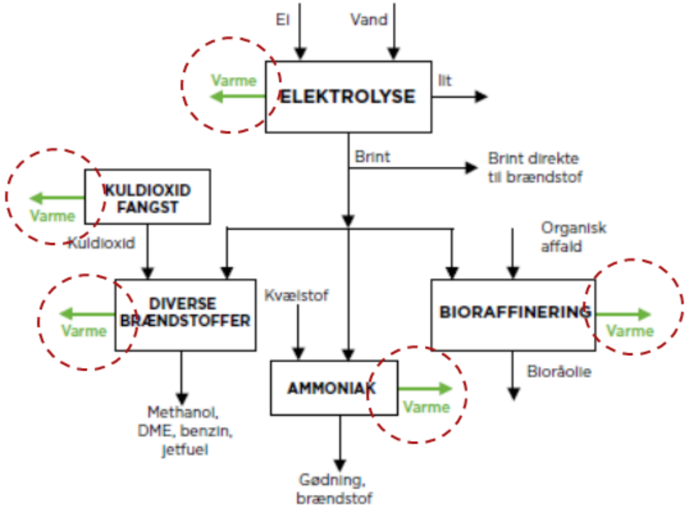
Source: EA Energianalyse, 2020 [Link]

DANISH STUDY ON RELATION BETWEEN PTX AND DH

TECHNICAL POINTS

- Production of hydrogen (/PtX) and CC(U)S will result in a lot of energy being lost as heat
- The share and temperature of heat loss varies greatly depending on technology and setup

Example of various PtX processes – and where heat is lost



Source: Power-to-X and district heating, Danish Association of District Heating, 2021

Electrolyser examples ("green hydrogen")

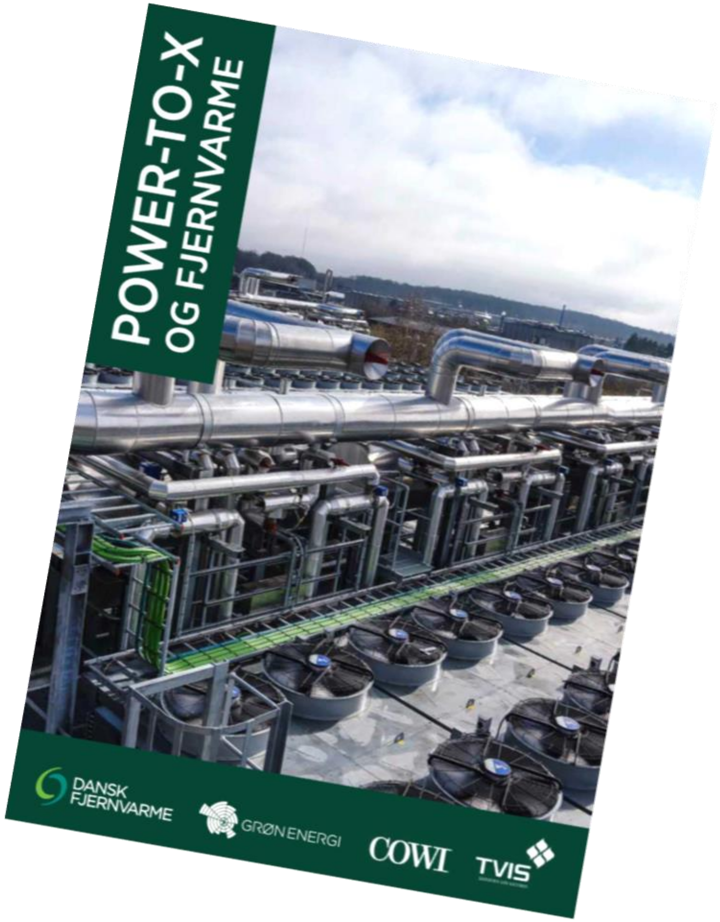
Technology	Operation	Input	Output	Efficiency	Relevant for DH
AEL	65-90 ºC 1-35 bar	Electricity Water	H2 O2 Heat	65% H2 (LHV) 10% DH 25% heat loss	Yes
PEM	50-80 ºC 1-50 bar	Electricity Water	H2 O2 Heat	64% H2 (LHV) 10% DH 26% heat loss	Yes
SOEC	>600 ºC 1-10 bar	Electricity Water Heat	H2 O2 [Heat]	75% H2 (LHV) 7% DH 18% heat loss	Less so

Source: Power-to-X and district heating, Danish Association of District Heating, 2021

...DANISH STUDY CONTINUED

KEY POINTS

- 10-25% of the energy used for PtX will end up as excess heat
- This excess heat is suitable for DH and could cover 20% of all DH in DK by 2030 (at 6GW hydrogen production)
- Recovery of heat can contribute to the success of hydrogen
- Recovery of heat from hydrogen strengthens sector integration



Source: Power-to-X and district heating, Danish Association of District Heating, 2021

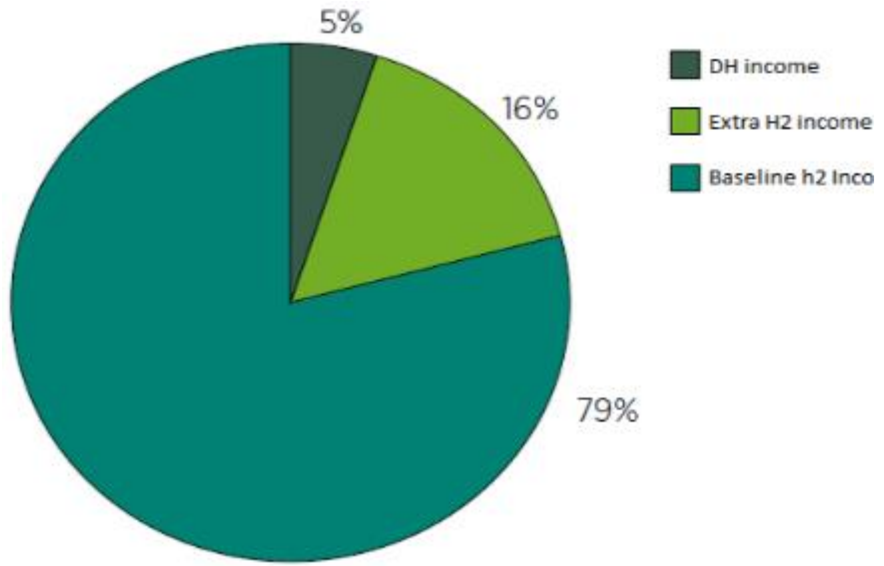
...DANISH STUDY CONTINUED

BENEFITS FOR HYDROGEN

- Extra income via sale of excess heat
- Sale of excess heat reduces cost of operation => additional operation hours => more H2 produced
- Provides possible savings on cooling CAPEX
- More energy efficient process – fewer losses – greener product – potentially higher price

BENEFITS FOR DISTRICT HEATING

- Attractive heat source:
  - High temperatures (relatively)
  - Many operational hours (stable)
  - Not based on combustion
- Expected to be widely available and close to big cities
- Synergies with CC on existing DH/CHP plants

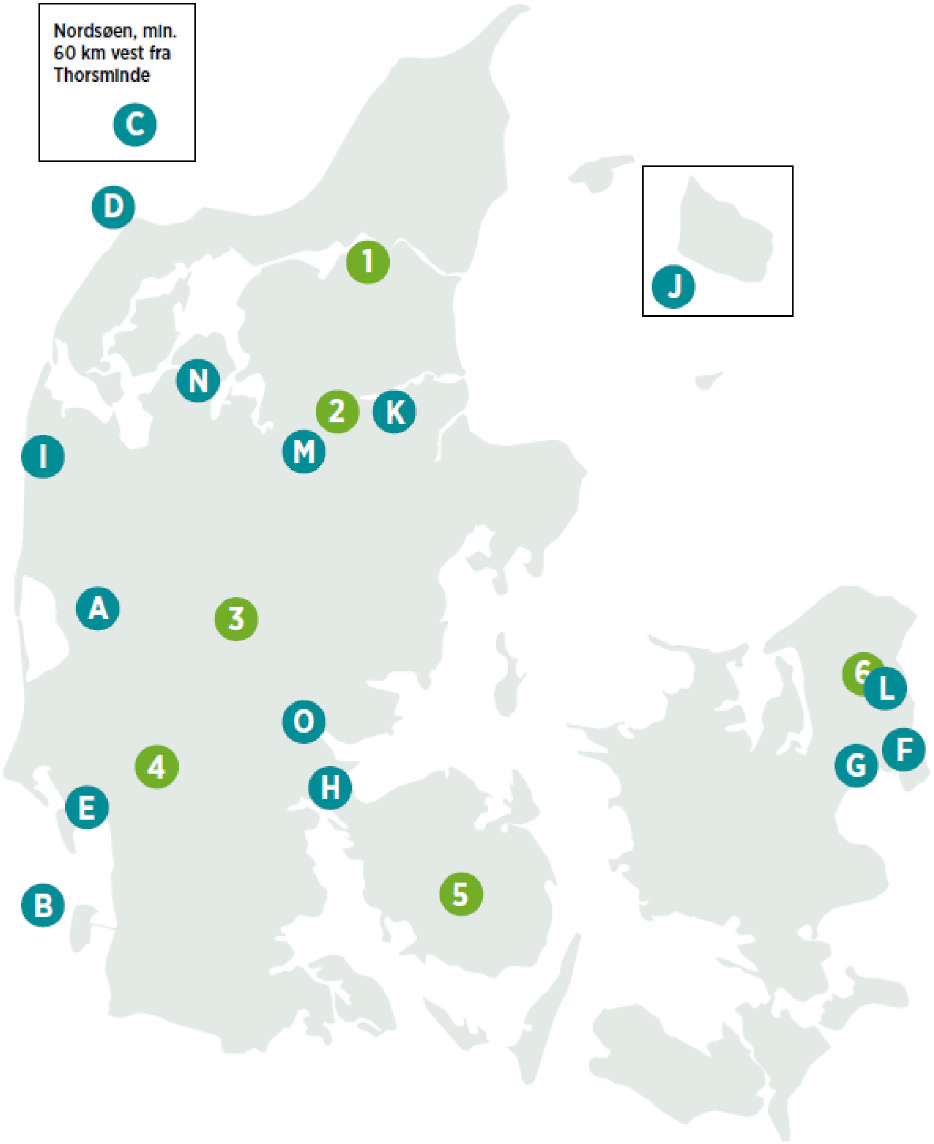


Example of distribution of income with heat recovery – case study of 20MW electrolyser.

Source: Power-to-X and district heating, Danish Association of District Heating, 2021

EXAMPLE OF DANISH CASES

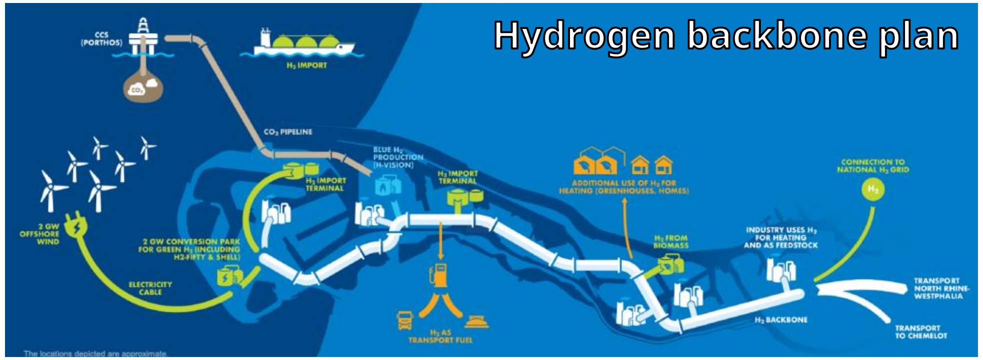
Where	Project	Partners	Capacity	Year (planned operation)	Heat recovery
(E) Esbjerg	Green hydrogen & ammonium production (for agriculture and shipping)	Copenhagen Infrastructure Partners, Arla, Danish Crown, DLG, Mærsk, DFDS	1GW	'26	Yes
(F) Copenhagen	Green Fuels for Denmark - Green hydrogen incl. carbon capture *(from other point source)* for fuel production	Ørsted, CPH Airport, Mærsk, DSV, SAS	10 MW (demo)	'23	Yes
			250 MW	'27	
			1,3 GW	'30	
(H) Fredericia	HySynergy - Green hydrogen to replace fossil hydrogen	Everfuel, Shell (now XX), TVIS,	20 MW	'22	Yes
			300MW	'24	
			1 GW	'30	

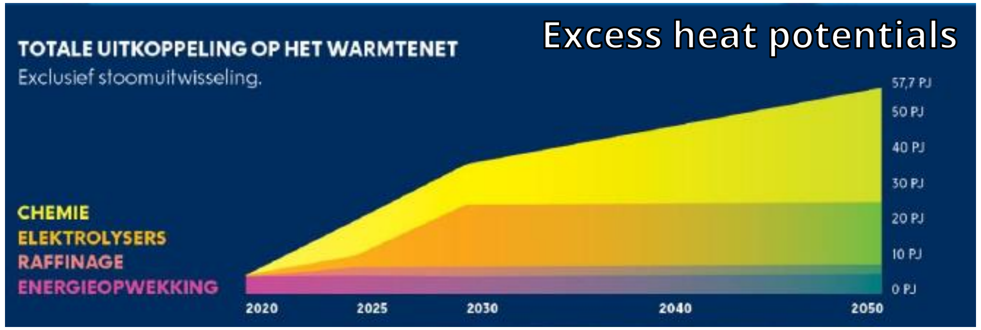


Source: Power-to-X and district heating, Danish Association of District Heating, 2021

PORT OF ROTTERDAM, THE NETHERLANDS

- Great ambitions for hydrogen – and district heating
- DH for up to 500.000 households (27 PJ) by 2030 - Today 5 PJ
- Heat recovery from electrolysers to play key role
  - 2023: 150-250 MW electrolyser
  - 2030: 2-2,5GW electrolyser
- Sees coordinated planning of infrastructure as key





Visuals and information from

Port of Rotterdam

THANKS FOR LISTENING – ANY QUESTIONS?

STUDY OBJECTIVES

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STUDY OBJECTIVES

Review existing and proposed Hydrogen and Heat network projects to:

- *Create a Vision and Associated Narrative for Hydrogen with Heat Recovery*

  Noting the likely development of Hydrogen clusters, the Study will provide local policy makers with a vision and narrative for engaging in sustainable heat planning

- *Highlight Potential Investment Opportunities for both Hydrogen and Heat Network Investors*

  The Study will highlight the immediate and potential future applications and opportunities

- *Re-Capture and Solidify Wider Interest in Waste Heat Recovery*

  Noting the political attention granted to Hydrogen, the Study is a novel way to re-capture and / or solidify wider interest in waste heat recovery, with also commenting on the policy barriers that still exist.

The Results of the Study will also be of interest to Policy Makers and Hydrogen and Heat Network Investors outside the UK

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TECHNICAL OVERVIEW

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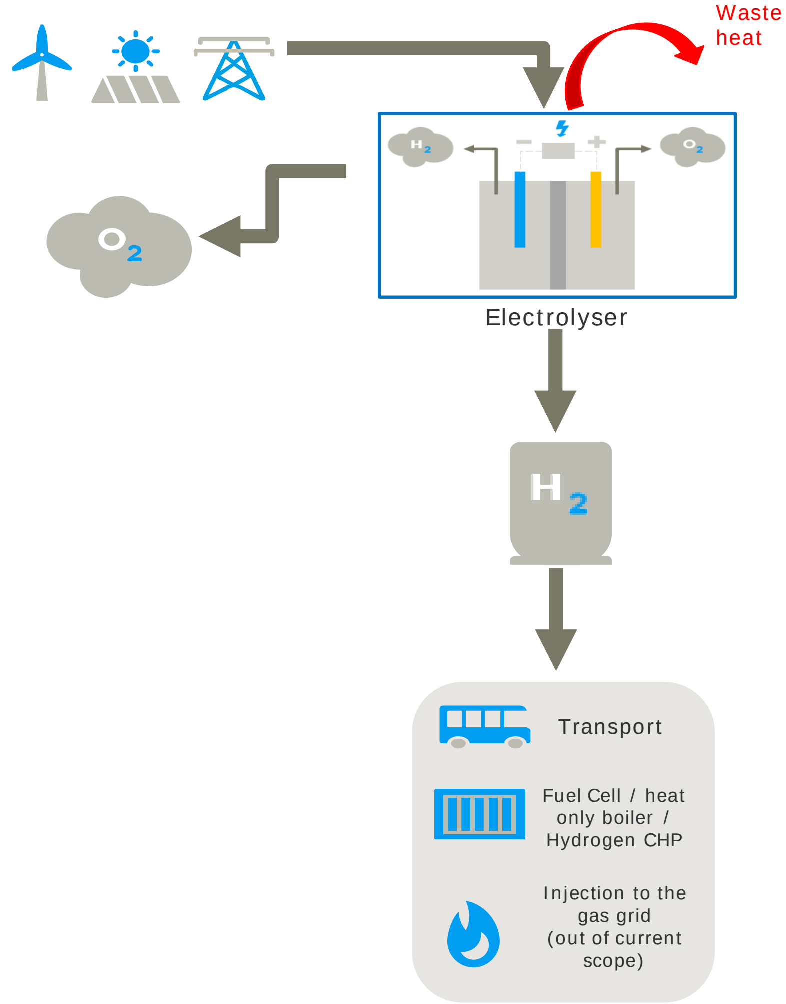
HEAT POTENTIAL FROM GREEN HYDROGEN

- In green hydrogen production hydrogen is produced by splitting water molecule into hydrogen and oxygen by using electricity
- Electricity supplied to electrolyser is more than the energy required for isothermal reaction and as a result waste heat is produced
- Depending on the type and design of electrolyser quantity of waste heat released can vary between 17% to 22% and the temperature of waste heat recovered can vary between 40°C to 77°C
- In 2050 it is estimated that the waste heat available from green hydrogen production can supply up to 16% of UK's total space heating demand.



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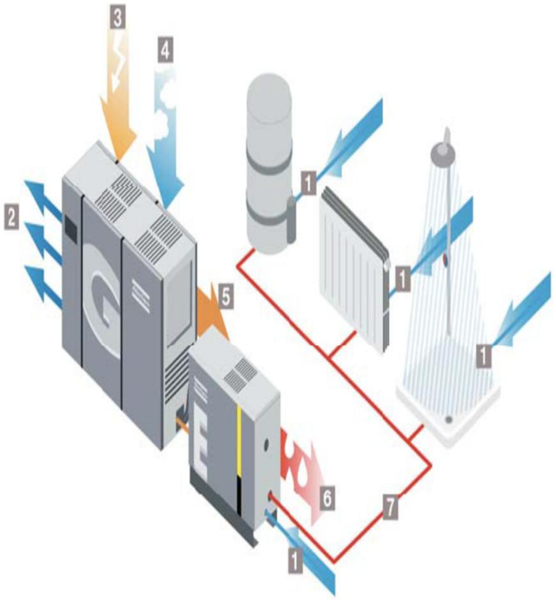
HEAT POTENTIAL FROM BLUE HYDROGEN

- Blue hydrogen production uses a feedstock such a methane (CH4) and high temperature (800°C) coupled with Carbon Capture and Storage (CCS) to produce low carbon hydrogen
- The core process which produces hydrogen is referred as Steam Methane Reformation (SMR) and for the most cases technology is provided by licensors.
- The process is complex and optimised over the years with heat recovery at various stages e.g. for steam generation, air heating etc.
- Since the SMR process is already optimised its potential to supply heat to DHN is questionable and needs further assessment on project to project basis.
- There is a good potential for heat recovery from auxiliary process such as cooling for CCS and compression. The heat recovery can result in significant power and water savings to the blue hydrogen projects.



1) Cold water 2) Compressed air 3) Electric power 4) Air 5) Oil circuit 6) Energy recovery 7) Warm water

Diagram credit: Atlas Copco

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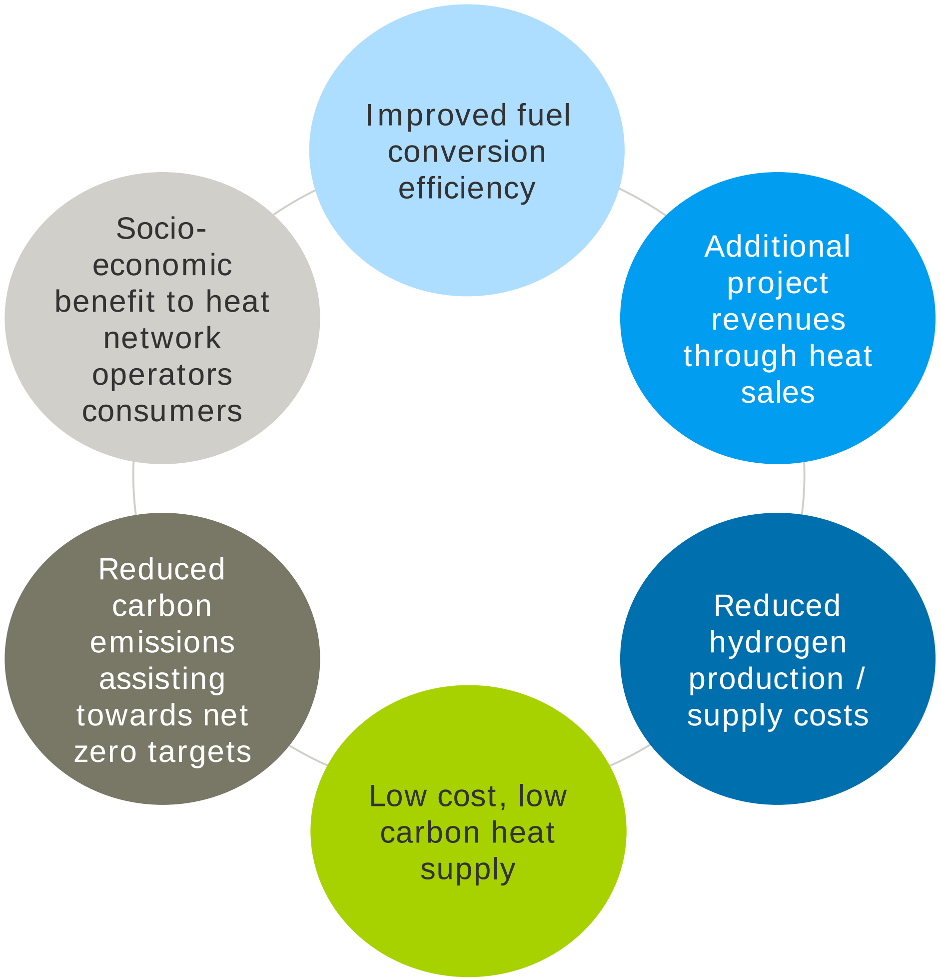
BENEFITS OF HEAT RECOVERY

HYDROGEN PRODUCERS / HEAT CONSUMERS



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INITIAL ANALYSIS AND APPRAISAL:

CONSIDERATION OF ENABLERS / BLOCKERS

Type	Enablers	Blockers
Technical	➢ Large H_2 Waste Heat Availability ➢ Good Heat Quality Supply (e.g. High Temp.) ➢ Large H_2 Growth Potential ➢ Sufficient Heat Demand ➢ Proximity to heat networks ➢ Density of heat demand ➢ Low Network Temperature	➢ Small H_2 Waste Heat Availability ➢ Low / Poor Heat Quality Supply (e.g. Low Temp.) ➢ Small H_2 Growth Potential ➢ Incompatible Heat Demand ➢ Availability of Cost Effective Alternative Heat Sources ➢ High Network Temperature
Commercial	➢ Incentives for Hydrogen production ➢ Incentives to heat network operator ➢ High network fuel costs	➢ High capital investment ➢ Low network fuel costs ➢ Lack of stakeholder coordination/interaction
Policy	➢ Heat hierarchy implementation ➢ Proactive planning policies to support hydrogen and DHN synergies	➢ Undefined planning policies ➢ Government funding

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Any Questions?

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Break
10mins

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STUDY STATUS AND INITIAL FINDINGS

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METHODS

- The Synergy Study has considered three geographical locations:

  Humber Region, Aberdeen and Leeds

H_2 / Heat Network Identification and Mapping → **Identification / Characterisation of Synergies** → **Stakeholder Engagement (Workshops)** → **Opportunity (Synergy) Development and Appraisal** → **Report and Recommendations (Conference)**

H_2 / Heat Network Identification and Mapping

- H_2 Projects / Status
- Heat Network Projects / Status
- Heat Supply / Demand
- Basic GIS Mapping

Identification / Characterisation of Synergies

- Waste Heat Supply /Demand
- Visualisation
- Initial Analysis
- Identify Key Stakeholders

Stakeholder Engagement (Workshops)

- Present Case Studies
- Present Opportunities
- Establish Appetite
- Discuss Enablers / Blockers

Opportunity (Synergy) Development and Appraisal

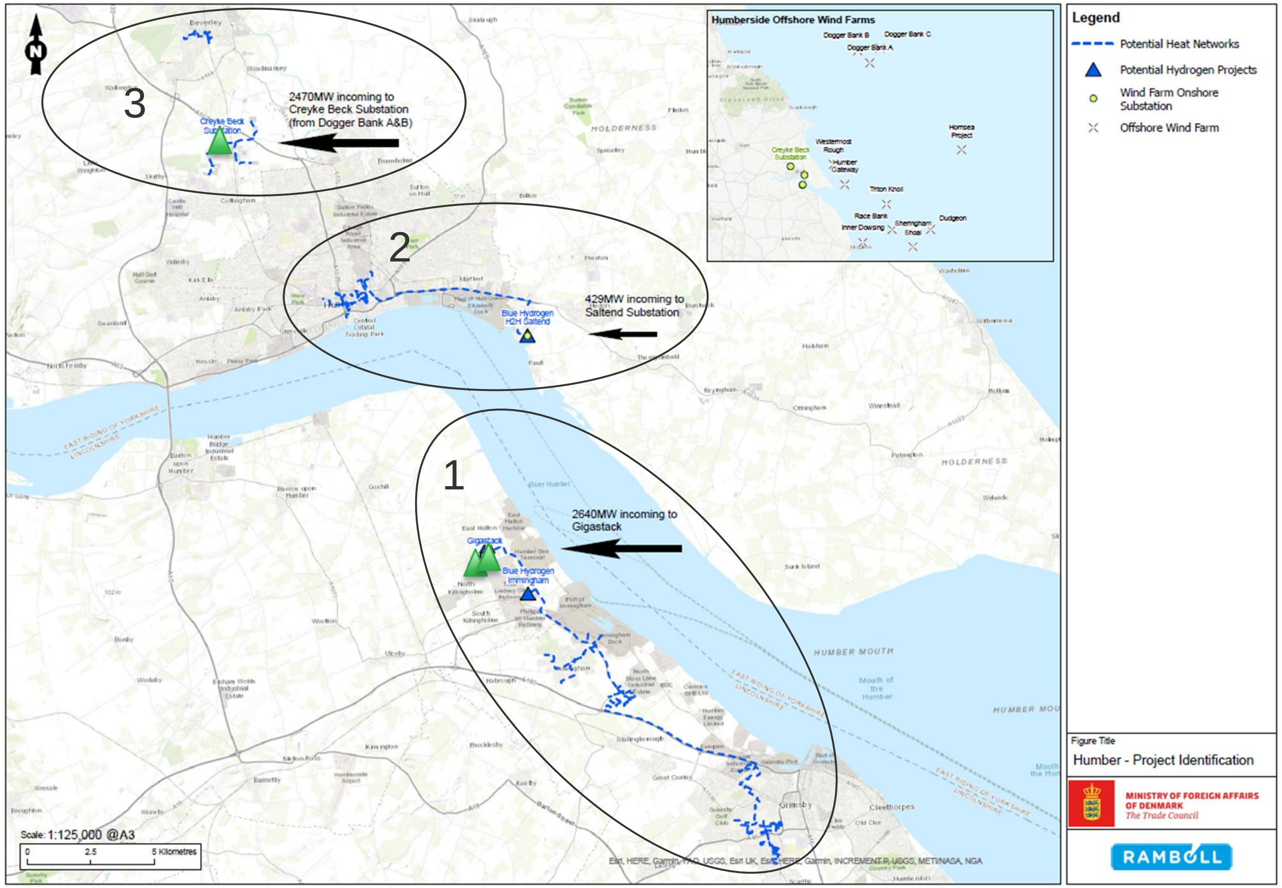
- Scale
- High-Level Costs and Benefits
- Commercial Delivery
- Next Steps?

OPPORTUNITIES (SYNERGIES) SUMMARY

Synergy Location	Actual District Heating Demand (MW)	Potential District Heating Demand (MW)	Estimated City-wide Heat Demand (MW)	Potential Waste Heat from Hydrogen (MW)	Potential Waste Heat from Hydrogen (Offshore Wind) (MW)
South Humber	0	42	125	58	330
Hull	10	10	350	18.5	5
Beverley	0	5	20	12.5	30
Aberdeen City Centre	11	20	210	2.7	13
Leeds City Centre	22	150	-	1.1	-

- Demand and supply peak analysis for each of the key areas investigated.
- Humber Region shows great potential in regards to hydrogen production with solid plans for DH networks in the coming years
- Aberdeen has a good balance of Hydrogen production potential with an existing District Heating Network, while also having large offshore wind farms which could further assist in additional Hydrogen production.
- Leeds has a large District Heating Network in place with aim to extend further, although there is currently limited Hydrogen production potential.

HUMBER REGION – GIS MAPPING



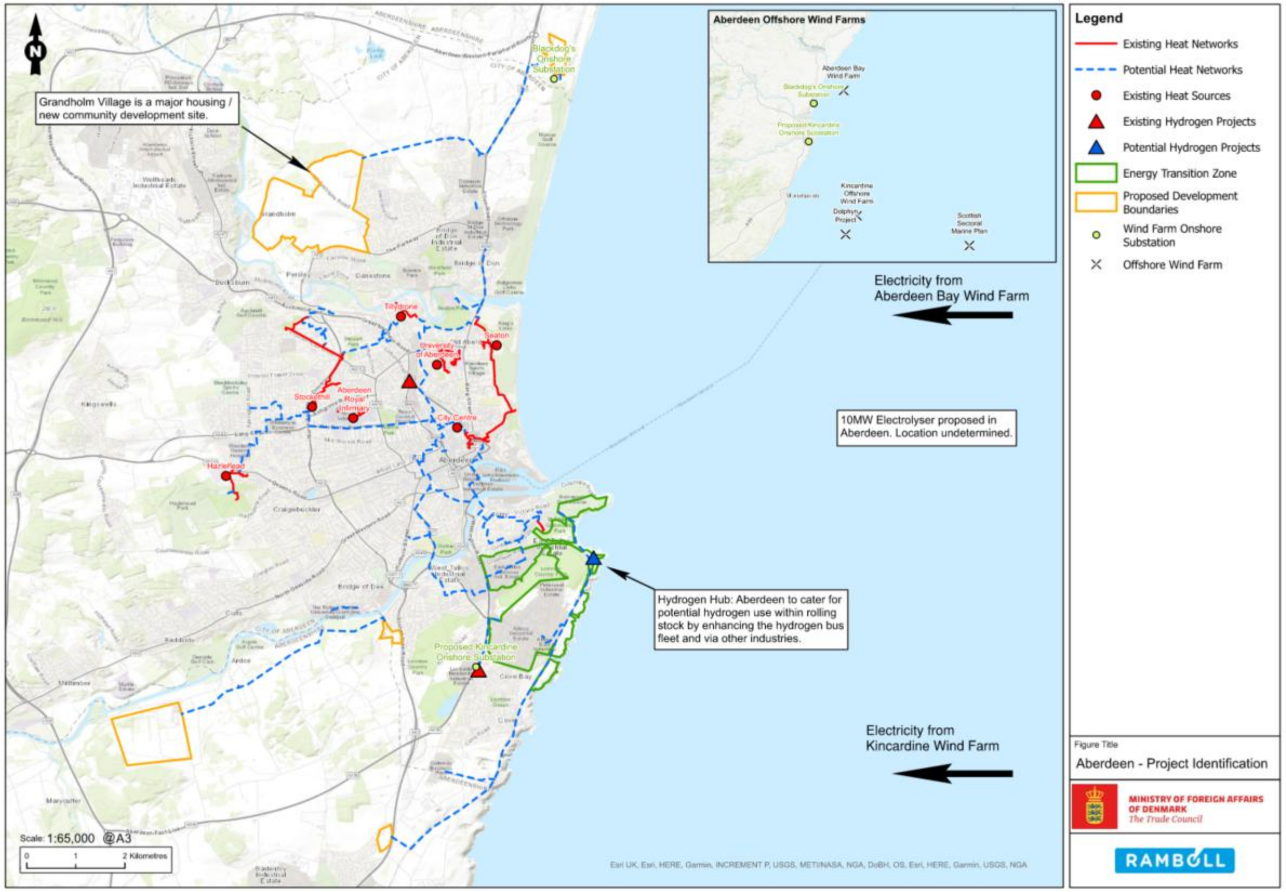
Three Synergies have been identified in the Humber Region:

1) South Humber – Five proposed heat clusters close to the Giga Stack and Uniper Hydrogen Production facilities

2) Hull – Town centre network which could receive heat from the H2H Saltend facility

3) Beverley – Proposed DHN in the area along with Greenhouses which could be fed from the Equinor facility

ABERDEEN – GIS MAPPING

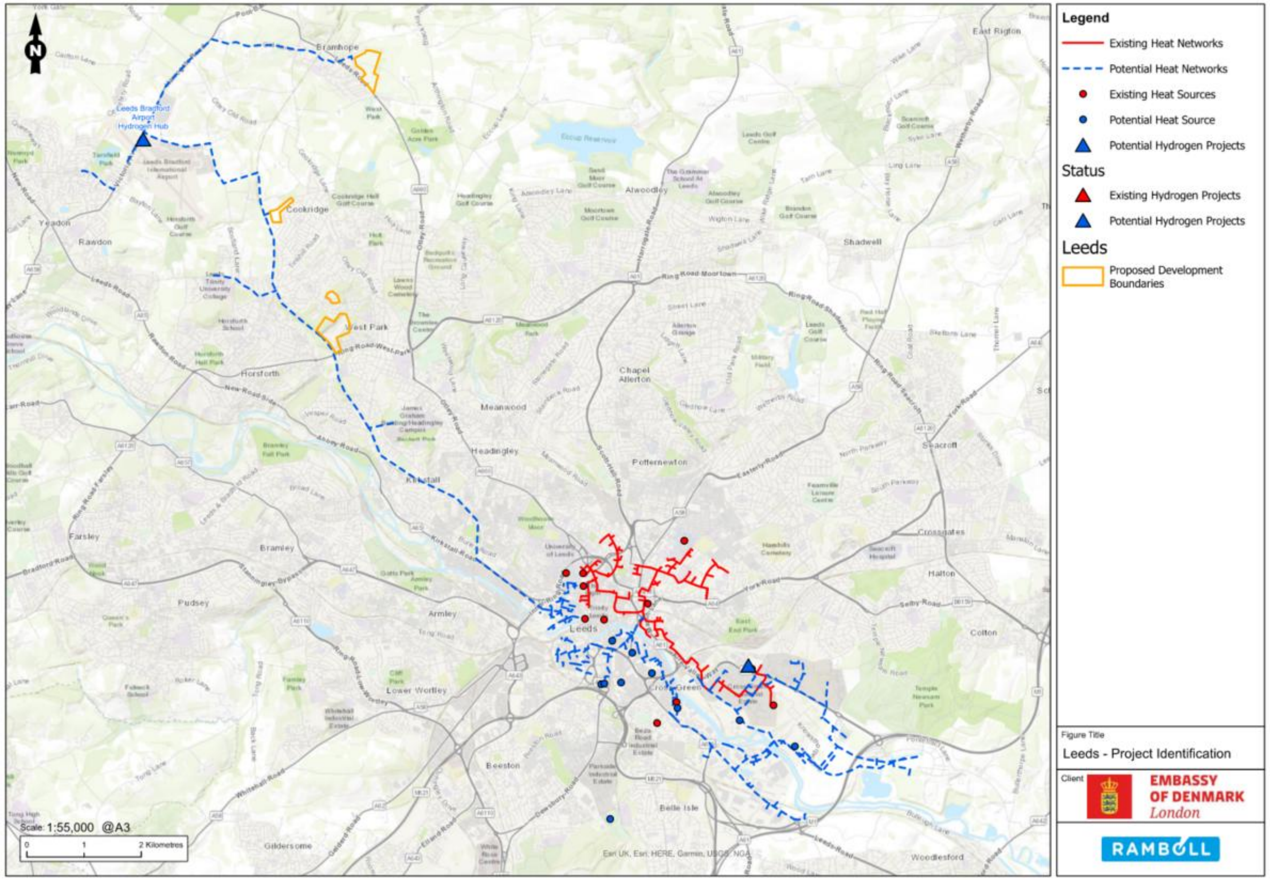


Aberdeen has a number of existing DH Networks operating across the city and aims to build a city wide heat network.

Through the H2 Aberdeen programme it is also on the forefront of Hydrogen production to create a hydrogen economy in the region.

Finally a number of offshore wind turbines already commissioned or currently under construction will generate renewable electricity which could be utilised for hydrogen generation as well.

LEEDS – GIS MAPPING



Leeds has a large DH network currently in place, with ambition to increase capacity up to 150MW in the future.

Currently plans for Hydrogen are very limited in the area with only Leeds Bradford Airport and Leeds Waste and Recycling Centre projects under consideration.

Definitely an area where hydrogen production could be investigated further however the current heat sources may limit the need for additional sources of heat.

PROPOSED ASSESSMENT CRITERIA

Proposed Criteria	Weighting	Comments
H_2 Heat Availability (max)	20%	Quantity of heat and intermittency
Heat Demand (max)	20%	DH Networks Existing and Planned
Distance	20%	Proximity of H_2 production to Network
Heat Quality (Temp)	10%	Grade of heat available from H_2 facility
Level of S/H Interest	10%	Engagement of Local/Private Stakeholders and Planning Authorities
Timescale to Implementation	10%	Concept/FEED/Planning/Development
H_2 Growth Potential	5%	Secured future waste heat
DHN Growth Potential	5%	Secured future heat load

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INITIAL APPRAISAL RESULTS

	South Humber	Hull	Beverley	Aberdeen City Centre	Leeds City Centre
H_2 Heat Availability (max)	5	5	4	3	1
Heat Demand (max)	4	4	3	5	5
Distance	4	3	3	4	4
Heat Quality (Temp)	2	2	2	2	2
Level of S/H Interest	3	4	2	4	2
Timescale to Implementation	4	4	2	5	1
H_2 Growth Potential	4	5	4	5	2
DHN Growth Potential	4	4	2	5	5
Scoring	3.90	3.85	2.90	4.00	2.85

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DATA GAPS

Synergy	Data gaps
S1 - South Humber	Confirmation on Blue Hydrogen waste heat assumptions
S2 - Hull	Confirmation on Blue Hydrogen waste heat assumptions Information related to heat demand
S3 - Beverley	Confirmation on project development and size assumptions Information related to heat demand
S1 - Aberdeen City Centre	Clarification of H2 project location details
S1 - Leeds City Centre	Development of H2 project development and size assumptions

Questions & Discussion

Enablers & Blockers
Assessment Criteria
Appraisal Results

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NEXT STEPS

NEXT STEPS…

- Ramboll Energy will collate the information from todays discussions and update the technical assessment criteria / scoring matrix.
- Subsequently, Ramboll Energy will re-assess and down-select the synergies, on a technical basis, utilising the updated technical assessment criteria / scoring matrix.
- Within each synergy, the re-assessment will include the identification of potential conditions which are likely to increase technical and / or commercial viability.

- Present findings at Workshop 2.

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WORKSHOP 2

- Workshop 2 will present the outcomes of the reassessment and down-selection, and confirm the synergy which will be taken forward for further commercial assessment / review.
- Workshop 2 will also highlight and summarise any identified conditions which are likely to increase technical and / or commercial viability.

- Proposed Date – Mid July 2021.

FINAL CONFERENCE

- Sharing experiences and findings from the study with wider UK audience and government stakeholders – incl.
    - Danish cases and experiences
    - Experiences from Port of Rotterdam
    - Study findings
    - [panel discussion/roundtable]

- Proposed Date – Mid September 2021.

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Technical Workshop 2 (03/08/2021)

SYNERGY STUDY
HEAT RECOVERY FROM HYDROGEN PRODUCTION

Workshop 2

3 August 2021

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AGENDA

01 Welcome
Study Background and Objectives

02 Synergy Study Project Team

03 Technical Recap
with Additional Information Received

04 Synergy Recap
with Additional Information Received

05 Updated Technical Assessment
and Selected Synergy

06 Justification for, and Transferability /
Wider Applicability of Selected
Synergy

07 Outline for High-Level Commercial
Assessment ,
with Assumptions and Criteria

08 Next Steps,
including Final Conference

WELCOME
STUDY BACKGROUND / OBJECTIVES

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STUDY BACKGROUND

- Noting the UK Government's 2050 Net Zero target, there is an increasing focus on Hydrogen to provide a credible option for decarbonising the UK energy system.
- In March 2021, Ramboll Energy was appointed by the Danish Energy Agency to undertake a Synergy Study assessing potential links between Heat recovery from Hydrogen production for use in District Heating networks.
- Building on inspiration from similar synergies achieved in Denmark, the Study has focussed on the UK market due its ambitions timescale for Hydrogen production as well as District Heating Network (DHN) development and deployment.
- Where Hydrogen is produced, an amount of waste heat is also generated.
- This presents an opportunity for both:
  - The Hydrogen sector - to increase energy efficiency and revenue; and,
  - The District Energy sector – to capitalise on what otherwise would be vented to the atmosphere.

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POTENTIAL ROLE AND SCALE OF HYDROGEN AND WASTE HEAT

(UK PERSPECTIVE)

- For example, in a previous 2020 Study, Ramboll Energy identified that Hydrogen production could reach between 153 to 569 TWh by 2050.
- Assuming heat loss between 10 – 25% of input energy, depending on technology, the resulting amount of waste heat would be between 19 to 178 TWh.
- The 2017 UK Clean Growth Strategy estimated that 17% (32 TWh) of the UK Heat demand will be delivered through District Heating by 2050.
- Therefore, if all waste heat from Hydrogen production could be recovered, then it could potentially meet between 60 to over 550% of this demand, or between 10 to 95% of all UK Heat Demand.
- Hence, there is definitely a market to be investigated.

STUDY OBJECTIVES

Review existing and proposed Hydrogen and Heat network projects to:

- *Create a Vision and Associated Narrative for Heat Recovery from Hydrogen Production*

  Noting the likely development of Hydrogen / Industrial clusters, the Study will provide local policy makers with a vision and narrative for engaging in sustainable heat planning

- *Highlight Potential Investment Opportunities for both Hydrogen and Heat Network Investors*

  The Study will highlight the immediate and potential future applications and opportunities

- *Re-Capture and Solidify Wider Interest in Waste Heat Recovery*

  Noting the political attention currently granted to Hydrogen, the Synergy Study is a novel way to re-capture and / or solidify wider interest in waste heat recovery from industry, whilst also commenting on the possible policy barriers and driver that exist.

The Results of the Study will also be of interest to Policy Makers and Hydrogen and Heat Network Investors outside the UK

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SYNERGY STUDY
PROJECT TEAM

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SYNERGY STUDY PROJECT TEAM

Jacob Byskov Kristensen
Energy Policy Advisor

Jen Hearne
Project Manager

Guy Robertson
District Heating Lead

Emily Agus
Acting
Project Manager

Amey Karnik
Hydrogen

Dan King
Hydrogen

William David MacRae
Heat / Hydrogen

Ana Gonzalez Vega
Heat

Lisa Pardini
Heat

Aimilios Spinoulas
Heat

TECHNICAL RECAP

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WASTE HEAT POTENTIAL FROM HYDROGEN PRODUCTION

- *In Green Hydrogen production:*

  Hydrogen is produced using electricity in an electrolyser to split water (H_2O) molecules to produce Hydrogen (H_2) and oxygen (O_2).

  The electricity supplied to the electrolyser is more than the energy required for the splitting reaction. Therefore, waste heat is generated.

  Depending on the design / type of electrolyser, waste heat generated represents between 17 to 25% of the total input energy, at temperatures between 40°C to 77°C.

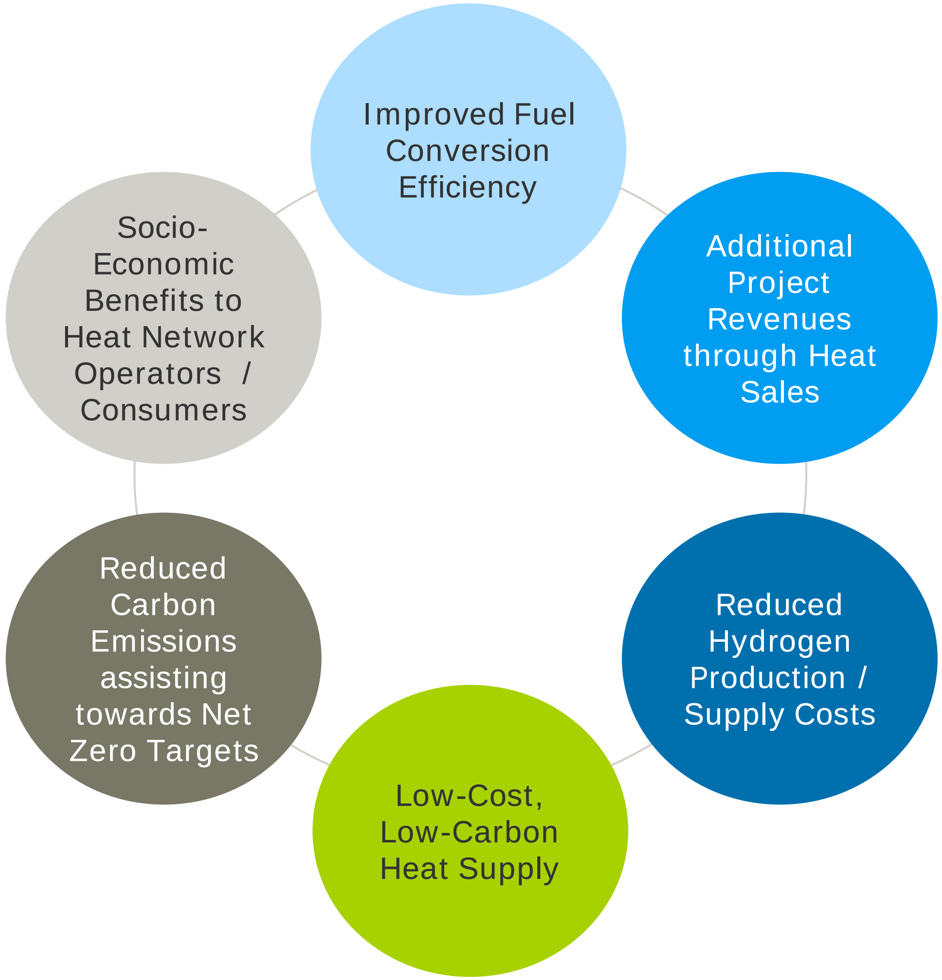
- *In Blue Hydrogen production:*

  Hydrogen is produced via a steam-methane reforming process, which mixes steam (H_2O) with methane (CH_4) to (ultimately) produce Hydrogen (H_2) and carbon dioxide (CO_2). For blue Hydrogen production, this process is coupled with CO_2 capture and storage to produce low-carbon Hydrogen.

  Whilst the core process is already optimised, there may be some potential for waste heat recovery from the auxiliary processes, such as cooling and CO_2 capture / compression.

  Such waste heat recovery needs further assessment on a project-to-project basis, and initial estimates of the waste heat generated and associated temperatures are highly variable.

BENEFITS OF WASTE HEAT RECOVERY



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SYNERGY RECAP

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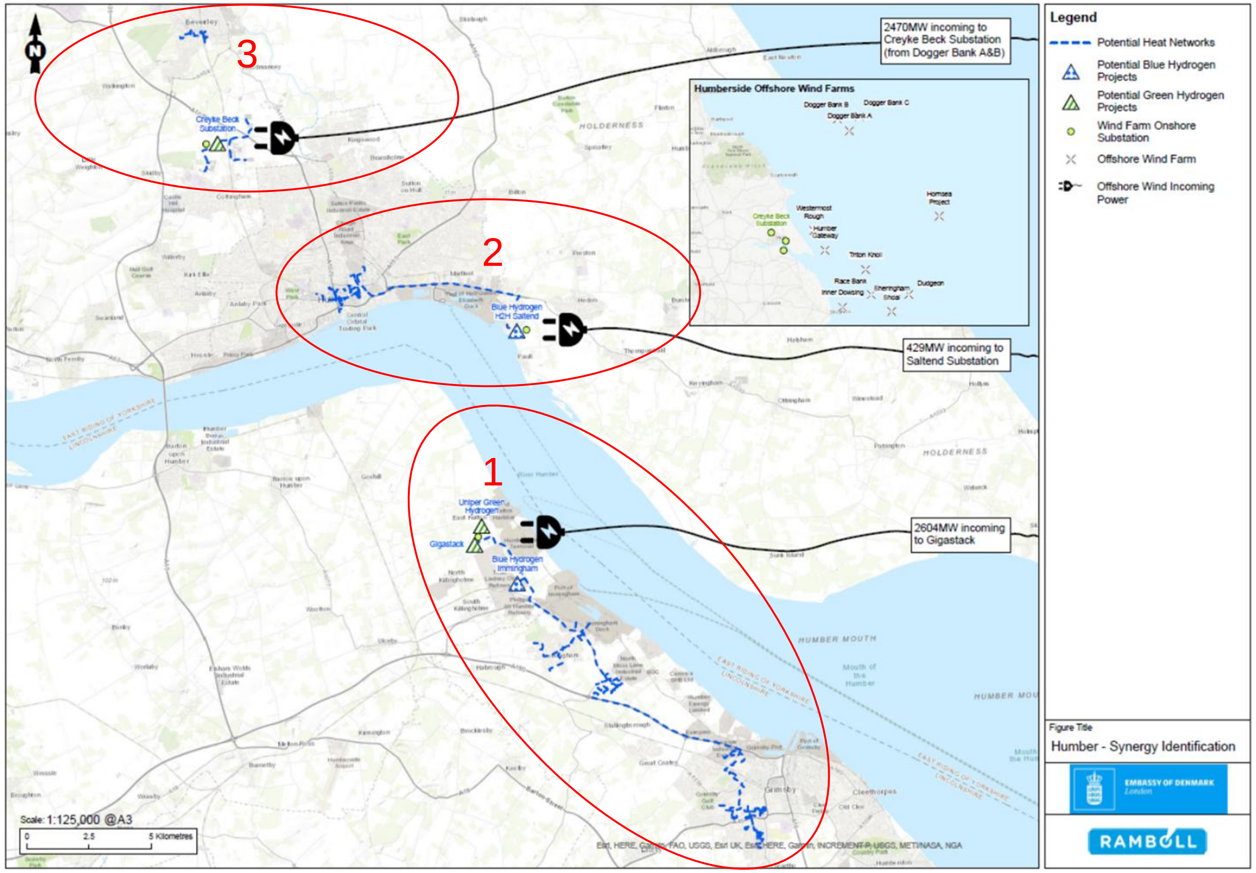
SYNERGIES SUMMARY

- Three Synergy Locations were considered:
  Humber Region; Aberdeen City Centre; and, Leeds City Centre.
- For each Synergy Location, the potential waste heat from hydrogen was determined, and a Heat demand and supply peak analysis was undertaken.
- Humber Region shows great Hydrogen production potential with solid plans for DHN in the coming years, while also having large offshore wind farms which could increase the Hydrogen production potential.
- Aberdeen has a good balance of Hydrogen production potential with an existing DHN, while also having large offshore wind farms which could increase the Hydrogen production potential.
- Leeds currently has limited Hydrogen production potential, but does have a large existing DHN with aims to extend further in the coming years.

SYNERGIES SUMMARY

Synergy Location	Existing / Committed District Heating Demand (MW)	Proposed District Heating Demand (MW)	Estimated City-wide Heat Demand (MW)	Potential Waste Heat from Hydrogen (MW)	Potential Waste Heat from (Offshore Wind) Hydrogen (MW)
South Humber	0	42	125	219	31
Hull	10	10	350	175	5
Beverley	0	5	20	11	30
Aberdeen City Centre	11	20	210	2.0	13
Leeds City Centre	22	150	300	1	-

HUMBER REGION MAPPING

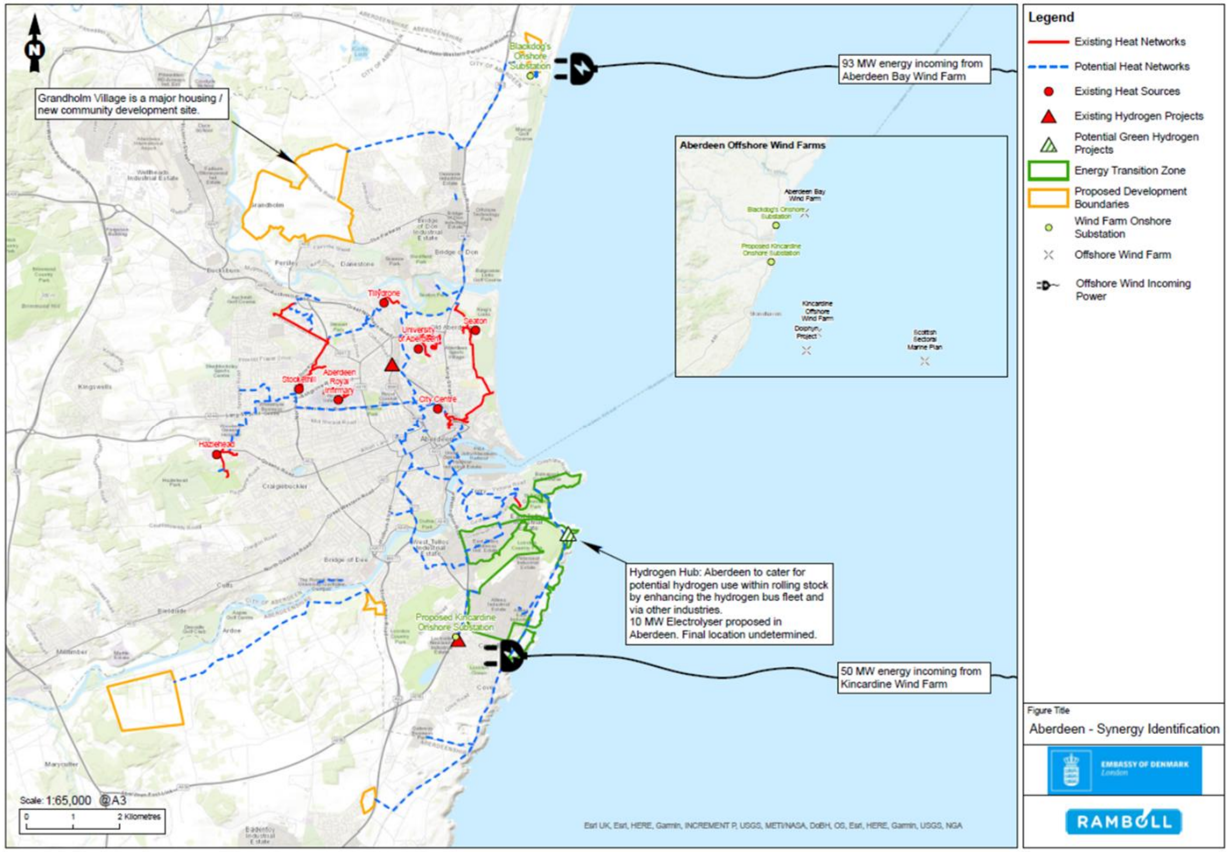


Three Synergies identified in the Humber Region:

1) South Humber –
   Five proposed Heat Clusters which could receive Heat from Giga Stack and Uniper Hydrogen production facilities
2) Hull
   Town centre DHN which could receive Heat from H2H Saltend Hydrogen production facility
3) Beverley
   Proposed DHN in the area along with Greenhouses which could receive Heat from Equinor Hydrogen production facility

In addition, a number of offshore wind turbines are already commissioned or currently under construction. These will generate renewable electricity which could also be utilised for Hydrogen production.

ABERDEEN MAPPING

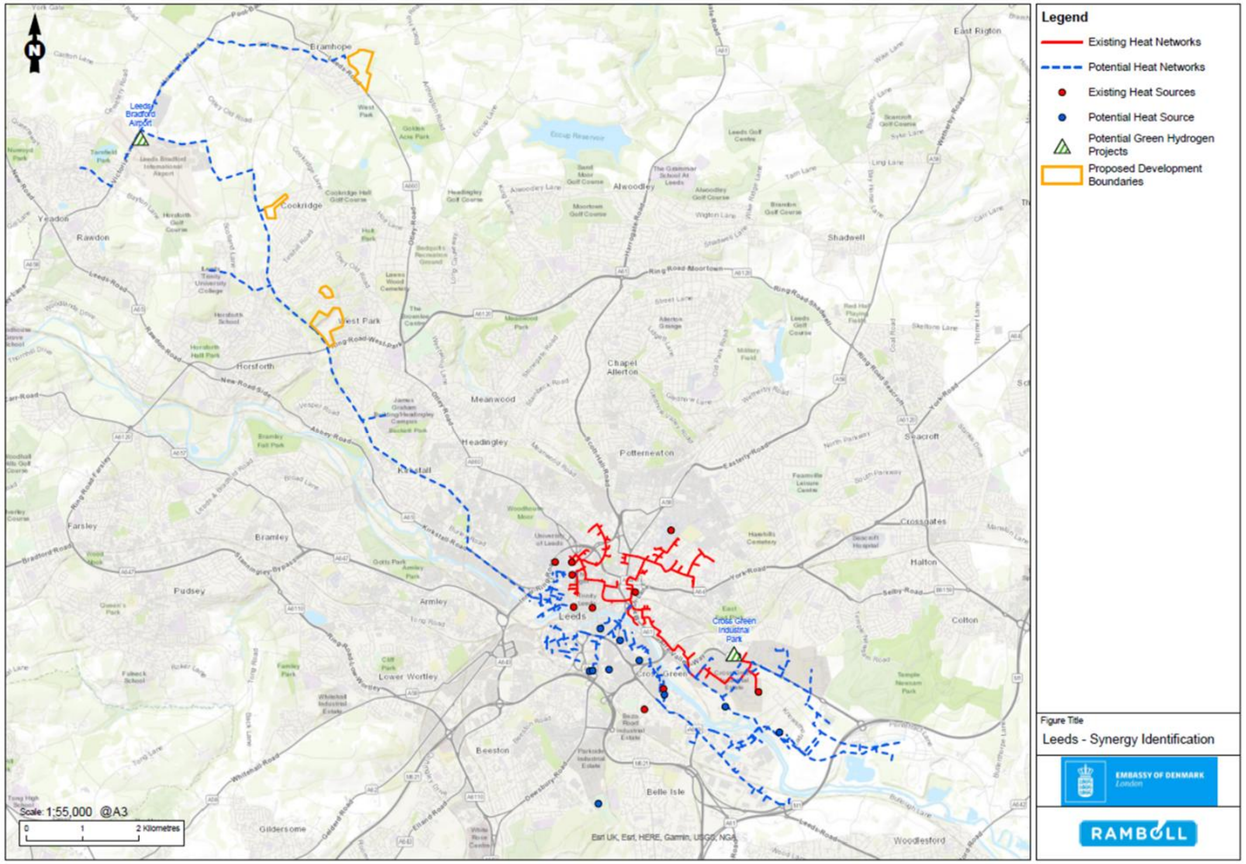


Aberdeen has a number of existing DHN across the city and aims to build a city wide heat network.

Through the H2 Aberdeen programme, Aberdeen is also on the forefront of Hydrogen production to create a hydrogen economy in the region.

In addition, a number of offshore wind turbines are already commissioned or currently under construction. These will generate renewable electricity which could also be utilised for Hydrogen production.

LEEDS MAPPING



Leeds has a large existing DHN, with ambition to extend capacity up to 150MW in the coming years.

Currently plans for Hydrogen production are very limited in the area with only Leeds Bradford Airport and Leeds Waste and Recycling Centre projects under consideration.

Definitely an area where Hydrogen production could be investigated further. However the current heat sources may limit the need for additional sources of heat (e.g. waste heat from Hydrogen production).

INITIAL ANALYSIS AND APPRAISAL:

CONSIDERATION OF ENABLERS / BLOCKERS

Type	Enablers	Blockers
Technical	➢ Large H_2 Waste Heat Availability ➢ Good Heat Quality (e.g. High Temp.) ➢ Large H_2 Growth Potential ➢ Sufficient Heat Demand ➢ Proximity to DHN ➢ Density of Heat Demand ➢ Low Network Temperature	➢ Small H_2 Waste Heat Availability ➢ Low / Poor Heat Quality (e.g. Low Temp.) ➢ Small H_2 Growth Potential ➢ Incompatible Heat Demand ➢ High Network Temperature
Commercial	➢ Incentives for Hydrogen Production ➢ Incentives to DHN Operator ➢ High Network Fuel Costs	➢ High Capital Investment ➢ Low Network fuel costs ➢ Availability of Cost Effective Alternative Heat Sources
Policy	➢ Heat Hierarchy Implementation ➢ Proactive Planning Policies to support Hydrogen and DHN Synergies	➢ Government Support ➢ Undefined Planning Policies
Other		➢ Lack of Stakeholder Coordination / Interaction / Interest

INITIAL TECHNICAL APPRAISAL CRITERIA

Initial Criteria	Weighting	Comments / Notes
H_2 Heat Availability (Max)	20%	Intermittency and Quantity of Waste H_2 Heat
Heat Demand (Max)	20%	Existing and Planned DH Networks
Distance	20%	Proximity of H_2 production to DH Network
Heat Quality (Temp)	10%	Grade of Waste H_2 Heat
H_2 Growth Potential	5%	Secured future Waste H_2 Heat
DHN Growth Potential	5%	Secured future Heat Load
Level of Stakeholder Interest	10%	Engagement of Local / Private Stakeholders and Planning Authorities
Timescale to Implementation	10%	At Concept / FEED / Planning / Development

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INITIAL TECHNICAL APPRAISAL RESULTS

	South Humber	Hull	Beverley	Aberdeen City Centre	Leeds City Centre
H_2 Heat Availability (Max)	5	5	4	3	1
Heat Demand (Max)	4	4	3	5	5
Distance	4	3	3	4	4
Heat Quality (Temp)	2	2	2	2	2
H_2 Growth Potential	4	5	4	5	2
DHN Growth Potential	4	4	2	5	5
Level of Stakeholder Interest	3	4	2	4	2
Timescale to Implementation	4	4	2	5	1
Scoring	3.90	3.85	2.90	4.00	2.85

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UPDATED TECHNICAL ASSESSMENT / SELECTED SYNERGY

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PROGRESS FROM WORKSHOP 1

- Ramboll Energy collated the information Workshop 1.

- Followed up with Stakeholders on Data Gaps.
- Followed up on additional project leads.

- Updated the Technical Appraisal Criteria, and the associated Appraisal Results.

- Selected a single Synergy to be taken forwards into the high-level Commercial Assessment.

INITIAL DATA GAPS, AND ADDITIONAL DATA RECEIVED

Synergy	Initial Data Gaps	Additional Data Received?
S1 - South Humber	Clarification on Blue Hydrogen Waste Heat Assumptions	
	Technical Details relating to Waste Heat from Electrolysers	✓
S2 - Hull	Clarification of Blue Hydrogen Waste Heat Assumptions	✓
	Information related to Heat Demand	
S3 - Beverley	Confirmation on Project Development and Size Assumptions	
	Information related to Heat Demand	
S1 - Aberdeen City Centre	Clarification of H2 Project Location Details	✓
S1 - Leeds City Centre	Development of H2 Project Development and Size Assumptions	

UPDATED TECHNICAL APPRAISAL CRITERIA

Initial Criteria	Weighting	Comments / Notes
H_2 Heat Availability (Max)	20%	Intermittency and Quantity of Waste H_2 Heat
Heat Demand (Max)	20%	Existing and Planned DH Networks
Distance	20%	Proximity of H_2 production to DH Network
Heat Quality (Temp)	10%	Grade of Waste H_2 Heat
H_2 Growth Potential	5%	Secured future Waste H_2 Heat
DHN Growth Potential	5%	Secured future Heat Load
Level of Stakeholder Interest	10%	Engagement of Local / Private Stakeholders and Planning Authorities
Timescale to Implementation	5%	At Concept / FEED / Planning / Development
Transferability	5%	Transferability of Study outcomes between locations

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INITIAL TECHNICAL APPRAISAL RESULTS

	South Humber	Hull	Beverley	Aberdeen City Centre	Leeds City Centre
H_2 Heat Availability (Max)	5	5	4	3	1
Heat Demand (Max)	4	4	3	5	5
Distance	4	3	3	4	4
Heat Quality (Temp)	2	2	2	2	2
H_2 Growth Potential	4	5	4	5	2
DHN Growth Potential	4	4	2	5	5
Level of Stakeholder Interest	3	4	2	4	2
Timescale to Implementation	4	4	2	5	1
Scoring	3.90	3.85	2.90	4.00	2.85

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UPDATED TECHNICAL APPRAISAL RESULTS

	South Humber	Hull	Beverley	Aberdeen City Centre	Leeds City Centre
H_2 Heat Availability (Max)	5	5	4	3	1
Heat Demand (Max)	4	4	3	5	5
Distance	4	3	3	4	4
Heat Quality (Temp)	2	2	2	2	2
H_2 Growth Potential	5	5	4	5	2
DHN Growth Potential	4	4	2	5	5
Level of Stakeholder Interest	4	4	2	4	2
Timescale to Implementation	4	4	2	5	1
Transferability	5	3	4	4	4
Scoring	4.10	3.80	3.00	3.95	3.00

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SELECTED SYNERGY

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SELECTED SYNERGY – SOUTH HUMBER

- South Humber has been selected as it has several large Hydrogen production projects under development, and existing plans for several DHN in the area.
- South Humber has two 100MW Green Hydrogen production projects one of which is in the FEED phase.
- This Synergy also has a Blue Hydrogen production project of 700 MW.
- Local authorities have commissioned a feasibility study for a number of DHN, with a heat demand of 42 MW and a potential city wide demand of 125 MW.
- The potential heating networks are in pockets moving outwards from the Hydrogen production facilities which offers a potential phased development opportunity.
- The analysis of this Synergy would have a potential benefit to all stakeholders within the other areas investigated as the analysis data can be adjusted to suit the different options available.

FACTORS GOVERNING THE SELECTION

- For the purpose of the Synergy Study, the information collected has relevance and is applicable and transferable to the others.
- When discussing the opportunities of Green and Blue Hydrogen, the waste heat potential was apparent in both processes and both production processes play an important role in the Hydrogen economy.
- The DHN development is at an early stage, therefore this allows more opportunity and less constraint on the technical parameters of the project, such as network temperature.
- Two separate manufacturers are selected for the Green Hydrogen projects, offering greater coverage of OEM configurations and heat interface requirements.
- Fewer technical constraints compared to the other locations.

TRANSFERABILITY OF THE DATA ANALYSIS

- The South Humber Synergy has both Green and Blue hydrogen production, meaning exploration of this Synergy has the potential to benefit all other Synergies. As previously noted, waste heat potential is apparent in both processes, and both production processes play an important role in the future Hydrogen economy.
- A large facility with scaled Hydrogen and DHN growth potential would benefit more projects and translate to a good case to provide an element of transferable and interchangeable data.
- Alternative cases are also able to benefit from this study by subtracting unnecessary elements (for example existing DHN vs new DHN).

DISCUSSION / QUESTIONS

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Break
10mins

OUTLINE FOR

HIGH-LEVEL COMMERCIAL ASSESSMENT

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PROPOSED METHODOLOGY

01 Hydrogen Project Scenario

- H_2 Project
- Waste Heat Available /
- Waste Heat Temperature
- Capacity Factor

02 Counterfactual Scenario

- Alternative Low / Zero Carbon Heat Source

03 Initial Technical Assessment

- Heat Demand
- DHN Temperature
- DHN Route / Sizing
- Heat Supply Strategy
- Energy Centre Location / Sizing

04 Techno-Economic Assessment

- CAPEX / OPEX / REPEX
- Revenues and Cash Flows
- Carbon Assessment
- Cost of Heat
- NPV,IRR, ROI

05 Sensitivity Assessment

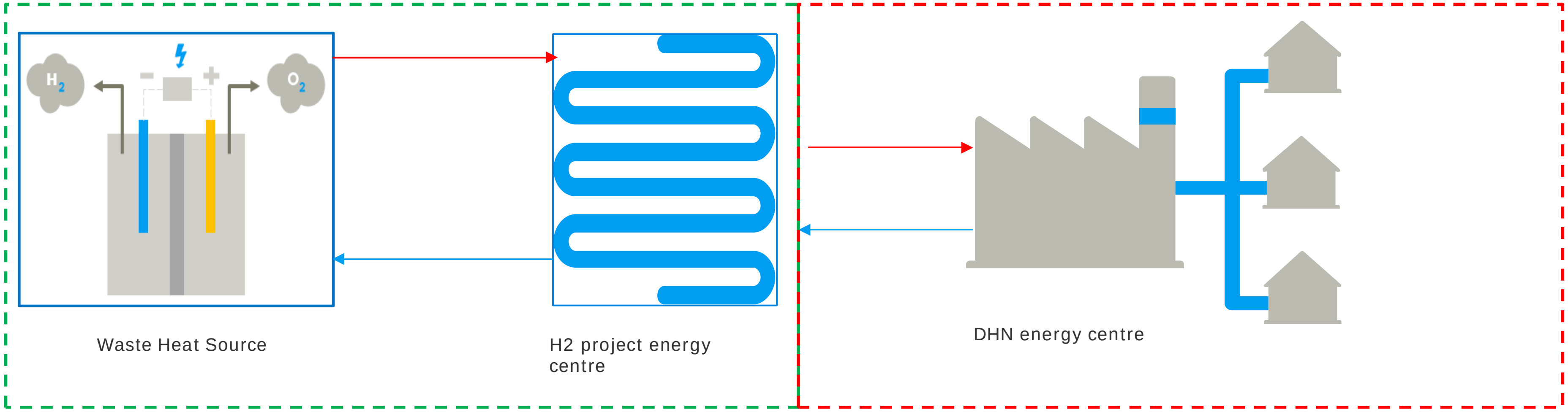
- Waste Heat Temperature
- Heat Demand
- DHN Temperature
- DHN Length
- H2 Capacity Factor/Waste heat availability
- CAPEX
- Heat Sale Rate

06 Impact Assessment

- Impact on H2 Projects
- Impact on DHN Projects
- Impact on Consumers
- Key enablers and blockers

SCOPE SPLIT ASSUMPTIONS

- Hydrogen and DHN Project Battery Limits



Hydrogen Project Scope:

- Heat Offtake Energy Centre at H_2 Project Site
- Heat Piping from Waste Heat Source to Heat Offtake Energy Centre

DHN Project Scope:

- Heat Piping from H_2 Project Energy Centre to DHN Energy Centre
- Heat Network from DHN Energy Centre OnwardS

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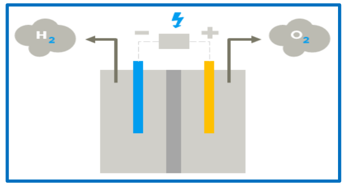
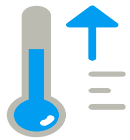
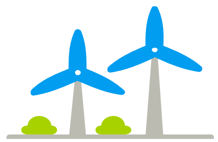
HYDROGEN PROJECT SCENARIO

- Location: South Humber
- Hydrogen Production Capacity
  - ➢ Green Hydrogen (For example, Gigastack or Uniper Green)
  - ➢ 20 MW
- Waste Heat Available
  - ➢ 4.4 MW (~22%)
- Waste Heat Temperature
  - ➢ 50 / 40°C
- Supply Temperature
  - ➢ 70 / 40°C
- Capacity Factor
  - ➢ 60%







COUNTER FACTUAL SCENARIO

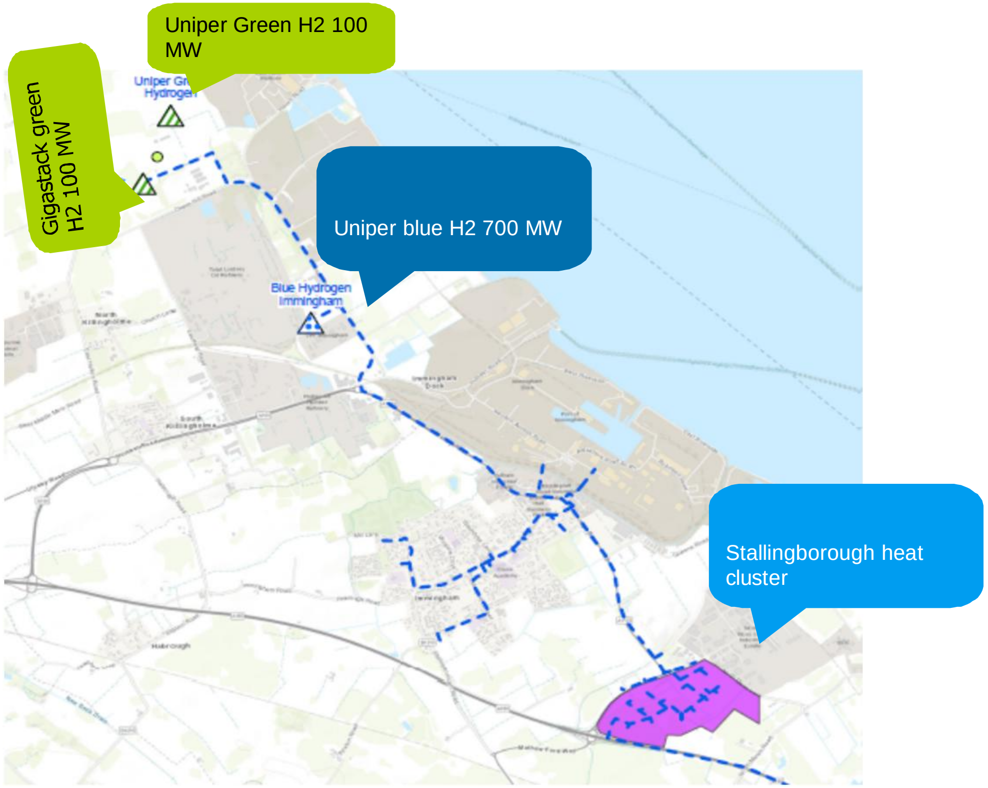
- Alternative Heat Source
  - ➢ Air-Source Heat Pump (ASHP); and / or
  - ➢ Water-Source Heat Pump (WSHP)

- Heat Supply Capacity (Heat Available)
  - ➢ 4.4 MW

- Supply Temperature
  - ➢ 70 / 40°C

HEAT DEMAND CLUSTER

- Location: South Humber
- Heat Cluster
  - ➢ Stallingborough Enterprise Zone
- Type of Demand
  - ➢ Commercial / Industrial
  - ➢ New Build / Future
- Peak Demand
  - ➢ 15 MW
- Annual Demand
  - ➢ 24,600 MWh
- Network Operating Temperature
  - ➢ 70 / 40°C



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SENSITIVITY ASSESSMENT

Parameter	Sensitivity
Waste Heat Temperature (to allow for both Green and Blue H_2)	+/- 30°C
Capacity Factor/Waste heat availability	+/- 40%
Heat Demand	+/- 50%
DHN Temperature	+/- 20 °C
DHN Length (Distance between H2 project and DHN)	+/- 50%
CAPEX	+/-50%
Heat Sale Rate	+/-50%
Grant / Funding Impact Assessment	0% to 50%

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QUESTIONS RAISED IN WORKSHOP 1

- Rule of thumb for cost of heat recovery from an electrolyser (p/KWh) (based on a given MW capacity) (e.g. as a comparator to other waste heat sources, such as EfWs)?
- Rule of thumb for how far it might be economic to transport heat recovered from (green) hydrogen production,?
- Rule of thumb for cost of heat delivered to a proxy energy centre in a city / town centre (p/kWh)? This will be a calculation of cost of heat recovery plus the cost of distributing the heat from the hydrogen production facility to the city / town centre (e.g. as a comparator to alternative solutions for the heat network developer).
- Indication of whole of life cycle costs?

DISCUSSION / QUESTIONS

NEXT STEPS

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NEXT STEPS...

- Ramboll Energy will collate the information from todays discussions and update the commercial assessment assumptions, methodology and scenarios.

- Present all findings at the Final Conference / Webinar.

FINAL CONFERENCE / WEBINAR

- To share the experiences and findings from the Synergy Study with a wide UK audience, including both industry and government stakeholders.
- To cover:
  - Current UK Heat Strategy;
  - Previous Case Studies and Experiences from Denmark and the Port of Rotterdam;
  - The Synergy Study Ambitions and Objectives;
  - The Synergy Study Findings, including the high-level commercial assessment; and,
  - The Recommendations and identified Gaps.
- Date – 28 September 2021, 9:00 to 12:00 (UK Time).
- We welcome your thoughts on holding an informal third Workshop, ahead of the Final Conference Webinar, to discuss the initial results of the commercial assessment.

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Final Webinar (28/09/2021)

SYNERGY STUDY

HEAT RECOVERY FROM HYDROGEN PRODUCTION

Final Webinar

28 September 2021

9:00 – 12:00 (UK Time)

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INTRODUCTIONS / OPENING REMARKS

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HEAT RECOVERY FROM HYDROGEN – UK STUDY

INTRODUCTION AND OPENING REMARKS
FINAL WEBINAR

Jacob Byskov Kristensen, Energy Counsellor – September 2021

CONTENT

- Welcome
- Energy Governance Partnership – Danish G2G
- The study background and motivation
- Todays programme and our speakers

HOUSEKEEPING

- We're recording
- Slides will be shared - final report available in October
- Expecting to finish early – plenty room for Q&A

Please;

- mute yourself when not speaking
- ask questions in chat or after each presentation ("raise hand")
- introduce and use camera when asking questions

WHO ARE WE?

Energy Governance Partnership (EGP)

- Government to government-program within Danish Governments *Global Climate strategy*.
- Provide experience, inspiration and support on the green transition of the energy system
- Supported by experts and resources in the Danish Energy Agency

MINISTRY OF FOREIGN AFFAIRS OF DENMARK
The Trade Council

Danish Energy Agency

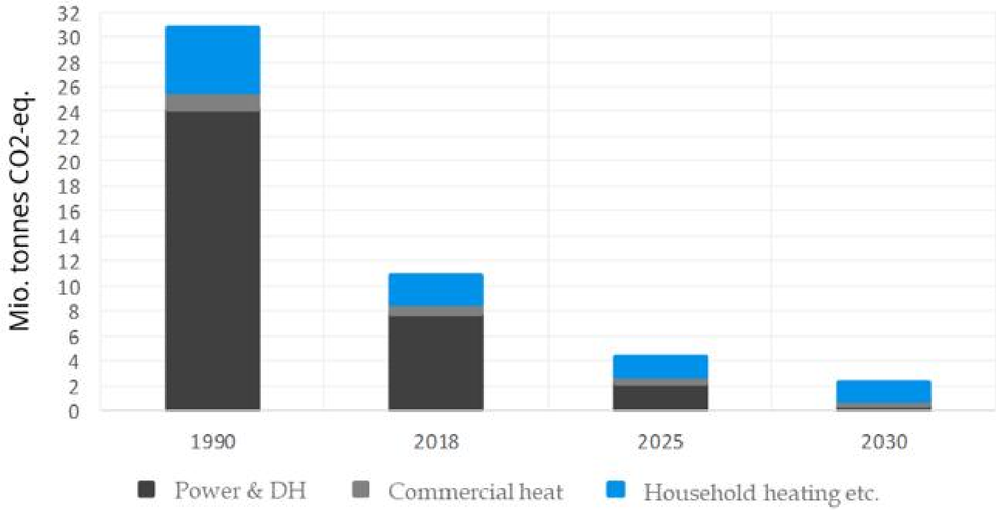
Jacob Byskov Kristensen, Energy Counsellor

- Danish Embassy in London
- Heading up the UK EGP Programme
- Former Danish Energy Agency, district heating office

WHY ARE WE HERE?

- Part of Danish Governments *Global Climate Action Strategy*
  - Speed up the global green transition by making Danish expertise and experience available
  - Partnerships with 19 nations / >65% of worlds total emissions
- UK have an ambitious climate agenda, but struggles to transform the heat and building sector – an area where Denmark is showing considerably more progress

Business-as-usual projection of emissions from power and heating in Denmark



Source: Danish Energy Agency, 2020

WHAT DO WE DO?

Programme activities – examples

- Close relation and **on-demand knowledge-sharing** with public officials in government
- **Study tours** for elected and public officials
- **Written evidence** for legislative and policy processes incl. public consultations
- Participation in **working groups**
- **Facilitating and financing**; conferences, studies, translation of documents etc.

Not just for policy makers: We gladly try to service anyone with questions and enquiries on Danish experiences, cases or contacts.

WHY THIS STUDY – FROM US?

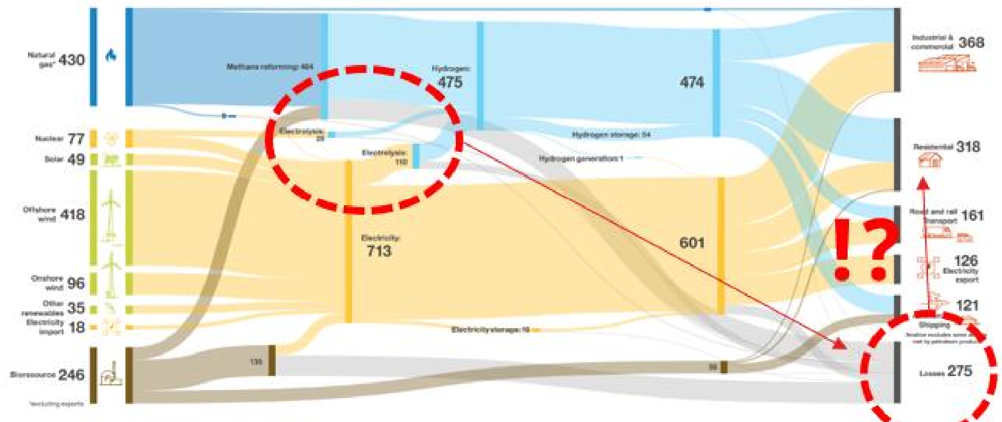
- Hydrogen absorbs a lot of attention – especially in the UK

- Little talk of the extensive energy loss – perhaps an overlooked opportunity?
  - UK Hydrogen strategy; up to 450TWH hydrogen demand
  - ≈112TWH(25%) energy lost as heat ≈25% of todays heat demand

- We believe Danish (and Dutch) cases and discussions could provide valuable insights and inspiration

- Initial analysis (2020) from Ramboll UK confirmed expected gaps and potential

National Grid simulation of 2050 UK energy system

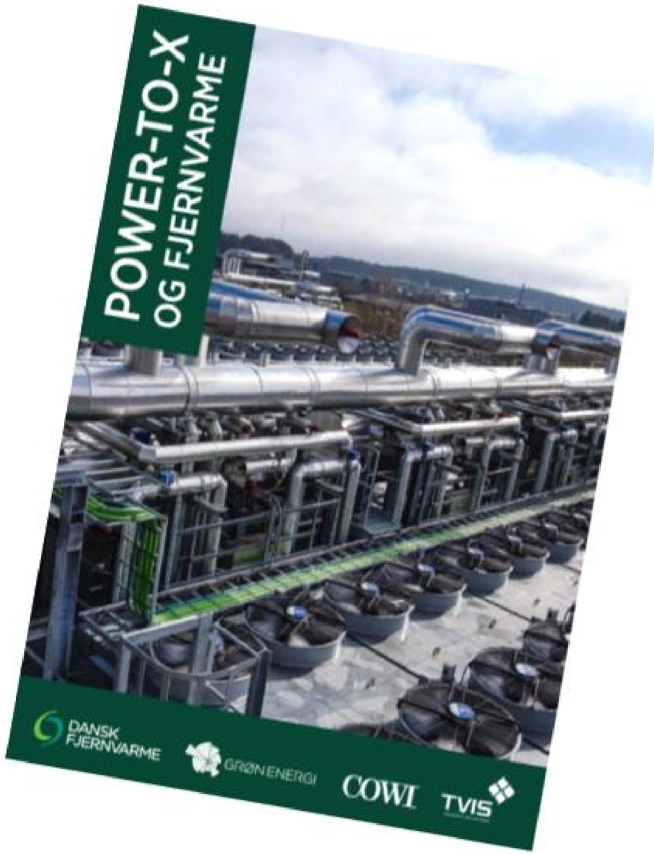


National Grid (2021) – UK Future Energy Scenarios [System Transformation, 2050]

DANISH STUDY ON RELATION BETWEEN DH AND PTX

KEY POINTS

- 10-25% of the energy used for PtX will end up as excess heat
- This excess heat is suitable for DH and could cover 20% of all DH in DK by 2030 (at 6GW hydrogen production)
- Recovery of heat can contribute to the success of hydrogen
- Recovery of heat from hydrogen strengthens sector integration



Source: Power-to-X and district heating, Danish Association of District Heating, 2021

STUDY OBJECTIVES

Through case studies and reviews of existing and proposed hydrogen and district heat projects - the study has to:

- ***Create a Vision and Associated Narrative for Heat Recovery from Hydrogen Production***
- ***Highlight Potential Investment Opportunities for both Hydrogen and District Heating Network Investors***
- ***Re-Capture and Solidify Wider Interest in Waste Heat Recovery***

Source: Power-to-X and district heating, Danish Association of District Heating, 2021

Today's Programme	
9:00 - INTRODUCTIONS AND OPENING REMARKS	
Introductions and Opening Remarks	Jacob Byskov Kristensen *Energy Policy Advisor [Project Owner]* Embassy of Denmark, UK
UK Government *Heat and Hydrogen Perspectives*	Joel Hamilton *Heat Network Specialist* UK Government (BEIS)
9:30 - EXPERIENCES AND INSPIRATION FROM OUTSIDE THE UK	
Heat Recovery from Hydrogen and PtX in Denmark: *Examples from the City of Fredericia*	Jørgen Nielsen *CEO* TVIS, Denmark
Heat Recovery Plans in the Port of Rotterdam, Netherlands	Randolf Weterings *Program Manager Electrification & Hydrogen,* Port of Rotterdam, The Netherlands
Q&A / Short Break	
10:30 – SYNERGY STUDY OF HEAT RECOVERY FROM HYDROGEN PRODUCTION IN THE UK	
Background and Technical Information	Rambøll Energy UK *Project Team*
Synergy Identification and Assessment, *& Recommendations*	Rambøll Energy UK *Project Team*
Q&A / Discussion	
CONCLUDING REMARKS - NO LATER THAN 12:00	

UK GOVERNMENT:
HEAT AND HYDROGEN PERSPECTIVES

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Joel Hamilton

Heat Network Specialist

UK Government,
Department for Business, Energy and
Industrial Strategy

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Heat Recovery from Hydrogen Production

Introduction: BEIS Perspective

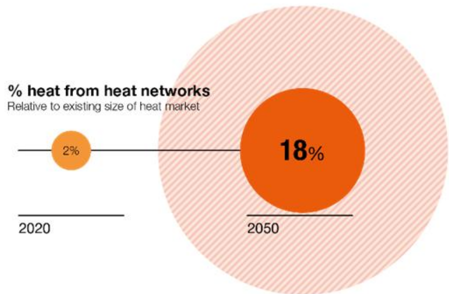
Dr Joel Hamilton
Heat network specialist
BEIS - Heat Networks Delivery Unit (HNDU)

30 September, 2021

Department for
Business, Energy
& Industrial Strategy

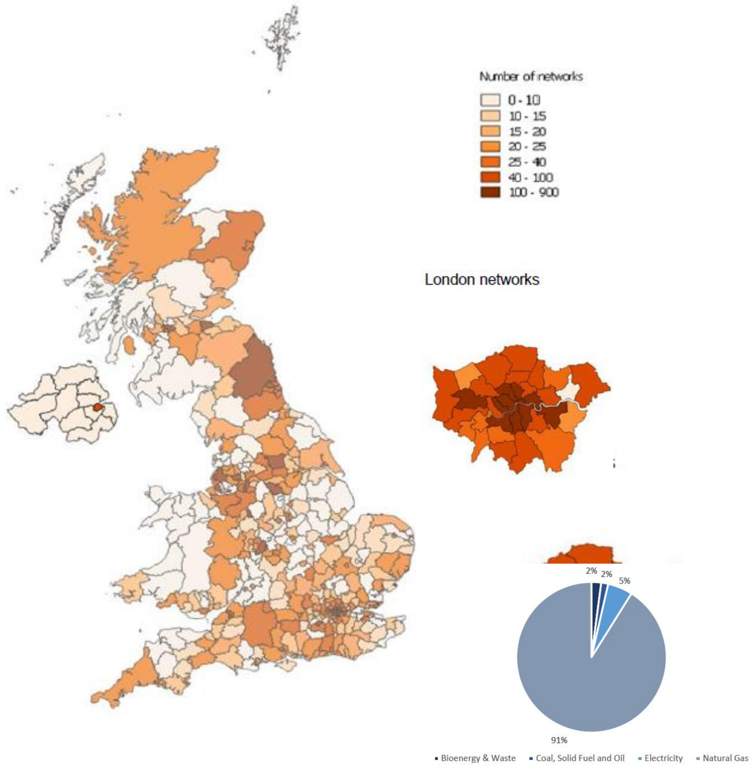
Importance of Heat Networks

- Today there are ~500,000 customers spread across 14,000 heat networks in the UK, of which ~2,000 are classed as district heating networks
- Heat networks currently provide 2% of UK heat demand and the Committee on Climate Change estimated in 2015 that with Government support, they could provide 18% of heat demand by 2050 in a least-cost pathway to meeting carbon targets. Our most recent research confirms this.
- Heat networks play a hugely important role in meeting carbon targets and reaching Net Zero.
- They can unlock otherwise inaccessible large-scale renewable and recovered heat sources such as waste heat from industry and heat from rivers and mines.



+10%

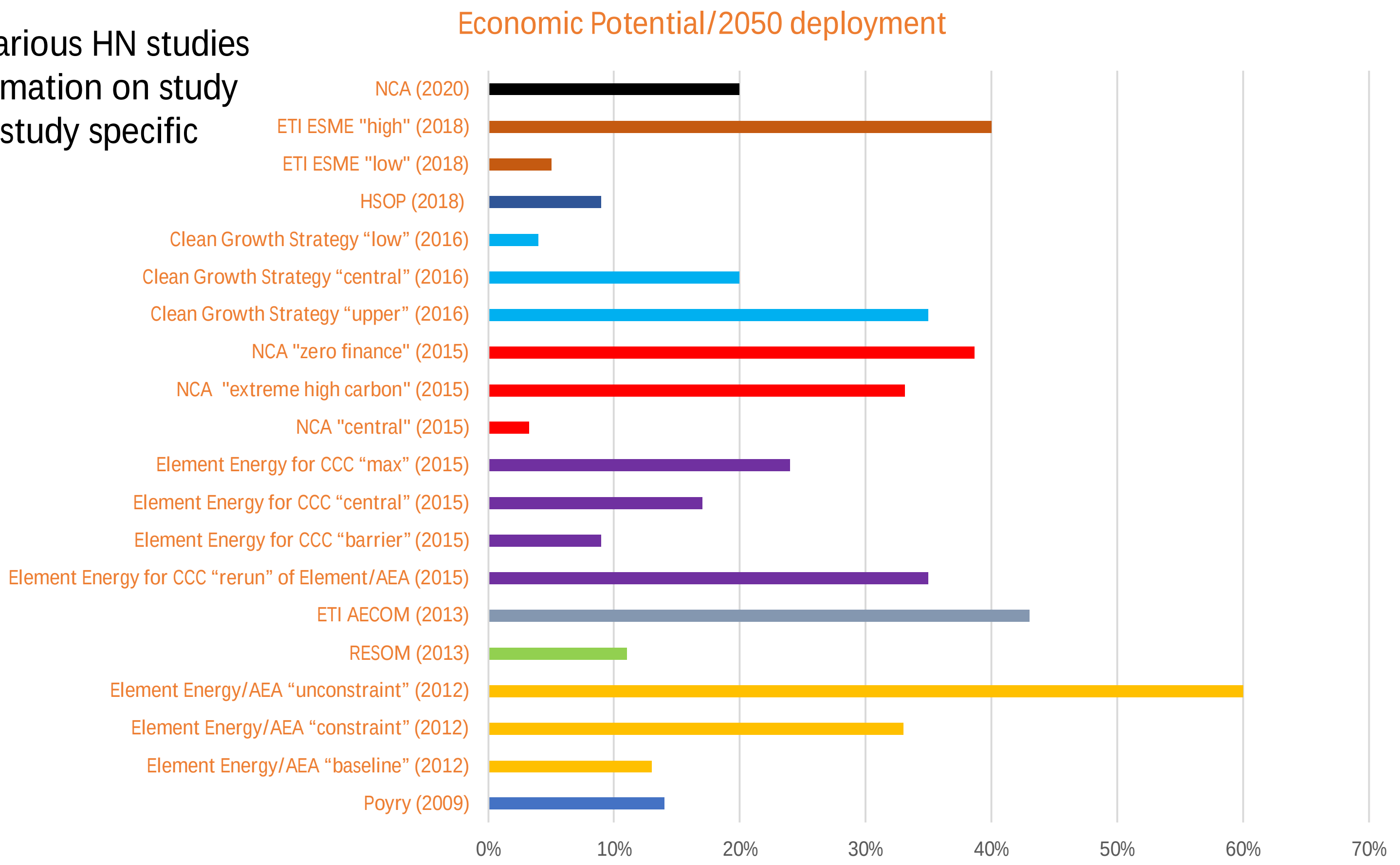
annual growth



BEIS (2018) Energy Trends: Experimental statistics on heat networks
(The experimental statistics may not wholly reflect the true position of the current heat network market due to networks not reporting or providing incorrect returns)

Positioning against other economic potentials

The Economic potentials from various HN studies are presented in the chart. Information on study approaches can be found in the study specific documentation.



Waste Heat Research

Aims

- To understand which sectors might have most potential in terms of scale, location and cost

Image: Petroac
https://renews.biz/66191/uk-project-explores-new-ways-to-recover-waste-heat/

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Targeted Sectors

Waste heat category (*)	Sub-sectors
Electricity substations	
Industrial heat recovery	Cement, Chemical, Crematoria, Food and drink, Iron and steel, Lime, Other mineral industries, Paper and pulp
Commercial heat recovery	Cold stores, Data centres, Supermarkets, Underground railways
Waste water heat recovery	Treatment works (narrative discussion about in sewer heat offtake, but not mapped)

** Note that Energy from Waste had been covered by a separate study and is not included in the results shown here.*

Output #1: location, temp and scale

Source type	Medium	Number of locations mapped	Assumed source temperature (°C)	Primary water temperature (°C)	Total peak heat capacity across all sites (MW)	Average installed heat recovery per site (kW)	Total heat available across all sites (GWh/year)	Average waste heat available per site (MWh/year)
Cement	Hot flue gas	10	338	90	69	6,863	469	46,945
Iron and Steel	Hot flue gas	27	120	90	195	7,227	1,539	57,018
Lime	Hot flue gas	6	338	90	13	2,213	91	15,139
Crematoria	Hot flue gas	269	900	90	75	280	157	585
Substations	Oil	1,336	45	40	479	359	3,989	2,986
Data centres	Water	264	35	30	1,940	7,347	16,153	61,187
Other mineral industries	Water	169	35	30	65	387	504	2,984
Chemical	Water	125	32	27	94	751	703	5,628
Food and drink	Water	142	30	25	41	289	307	2,164
Paper and pulp	Water	10	30	25	11	1,121	80	7,980
Supermarkets	Refrigerant	4,853	23	18	1,439	296	7,981	1,645
Cold stores	Refrigerant	241	23	18	517	2,143	3,469	14,394
Underground railways	Air	65	22	14	39	595	322	4,953
Treatment works	Water	1,875	18	13	2,929	1,562	24,379	13,002
	TOTAL	**9,392**			**7,906**		**60,145**	

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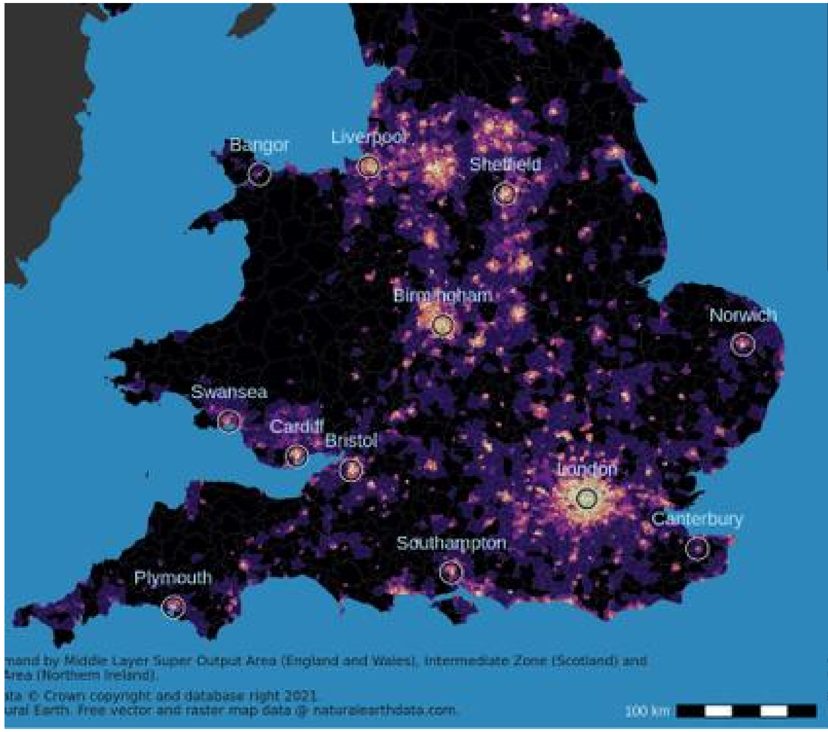
Output #2: typical cost of heat recovery

Source type	Primary water temperature (°C)	Average CAPEX benchmark (£/kW)	Average CAPEX per site (£'000)	Average OPEX per site (£'000/year)	Average LCOC (p/kWh)
Cement	90	238	1,514	178	0.55
Data centres	30	168	987	320	0.62
Treatment works	13	182	233	68	0.63
Other mineral industries	30	184	70	16	0.64
Chemical	27	183	127	30	0.65
Food and drink	25	184	53	11	0.65
Paper and pulp	25	184	196	42	0.65
Iron and Steel	90	568	1,516	211	0.78
Lime	90	495	1,066	66	0.78
Cold stores	18	634	976	58	0.85
Substations	40	828	285	10	0.90
Underground railways	14	834	483	24	0.95
Supermarkets	18	757	218	8	1.14
Crematoria	90	614	172	5	2.15

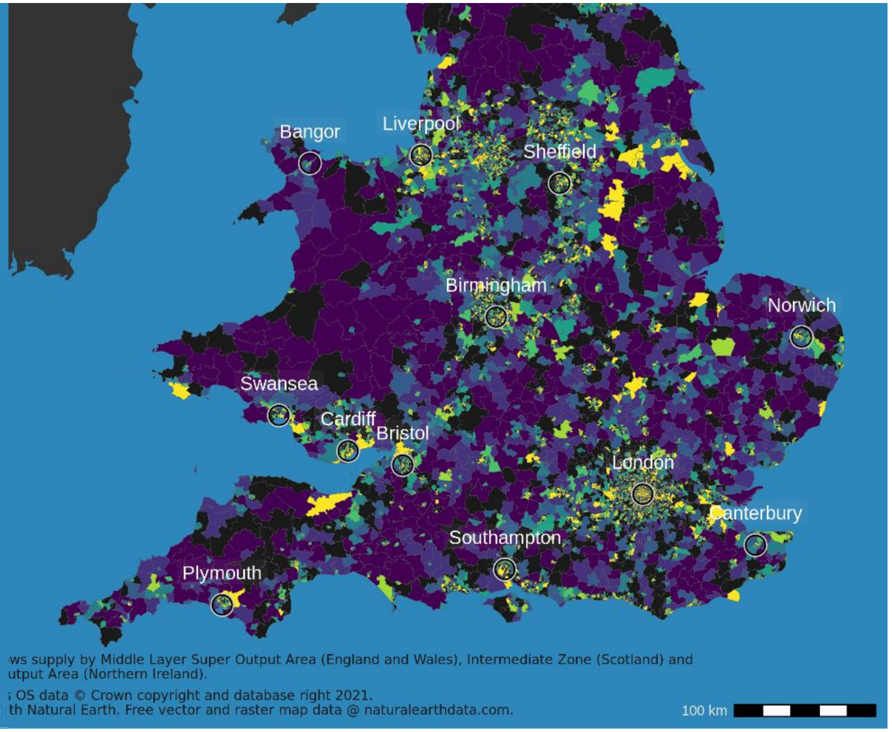
Although cost of capture may be low, some of these sources will need to be upgraded if they are to be used in a conventional heat network.

LCOC = Levelised cost of capture
CAPEX = Capital Expenditure
OPEX = Operational Expenditure

Output #3: Heat Demand and Supply



Demand



Supply

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Waste Heat Research Summary

- There is currently a lot of waste heat generated across the UK
- Different sectors have different characteristics in terms of:
  - The temperature of the heat
  - The technology required to capture it
  - Their location
- As a consequence the cost of heat recovery from different sectors is different.
- The geographic spread of heat across the UK does not align with that of demand everywhere but there are significant areas of overlap.

Hydrogen

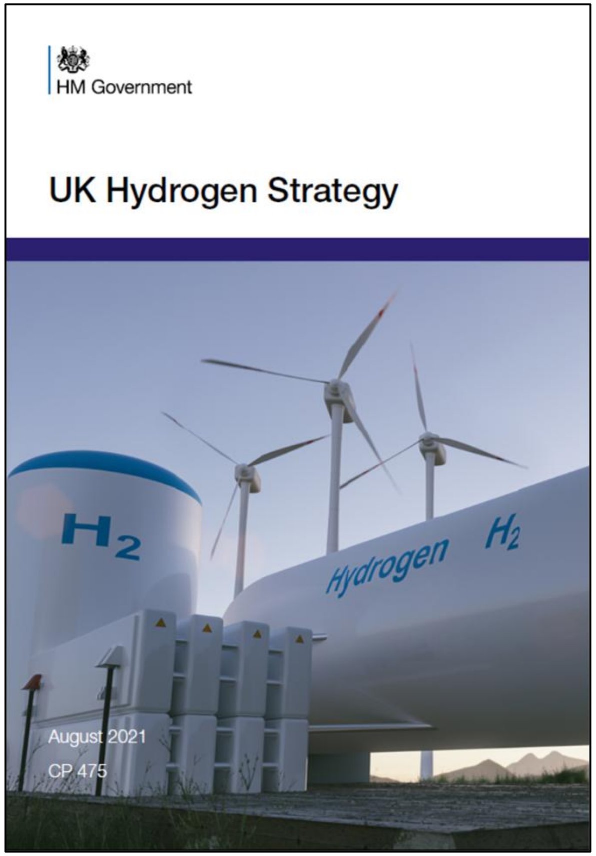
- Hydrogen is an important energy vector

  …but we need to be able to use it wisely

- Hydrogen production is going to be energy intensive

  …details on hydrogen production and uses will be described later

- Reducing the demand for hydrogen by using its waste heat will help sustainable resource allocation



Waste Heat from Hydrogen Production

- Hydrogen production and transportation will generate waste heat and coolth.
  - The process of **creating hydrogen will generate waste heat** which will need to be removed (cooled)
  - The process of **transporting hydrogen** will generate **heat when compressing** it and **coolth when expanding**
- In time efficiency improvements may reduce the amount of waste heat
- Laws of physics dictate that there will always be waste when transferring from one energy medium to another

Hydrogen and Heat Networks

- Heat networks are technology agnostic as they are an energy transmission system – *pipes and pumps*
- Hydrogen can be used in heat networks in the following ways:
  - Burnt in a boiler
  - Combined heat and power (CHP) either fuel cell or combustion engine
  - Storage medium chemical reactions releasing heat
  - Waste heat from hydrogen production
  - Waste heat from hydrogen usage

Department for Business, Energy & Industrial Strategy

Sustainable Resource Usage

- Reduce
  - Reduce the energy demand through energy efficiency

- Reuse
  - Reuse the energy in the process where possible

- Recycle
  - Use a heat network to take the waste heat to use it elsewhere

Complementary Workstreams

- Opportunity areas for district heating networks in the UK: second National Comprehensive Assessment
- Energy from Waste (EfW) study
- Waste heat from Water Sector
- Heat Network Optimisation Opportunities (HNOO) scheme
- Heat Network Transformation Programme
    - Green Heat Network Fund (GHNF), Market Framework, Heat Network Efficiency Scheme (HNES), Heat Network Investment Project (HNIP)
- City DEEP Decarbonisation Projects (CDDP)
- Greening Existing Networks (GEN)
- Industrial Heat Recovery Support Programme (IHRS)
- Industrial Energy Transformation Fund (IETF)

Thank you

To Embassy of Denmark London, Ramboll and other speakers

HEAT RECOVERY FROM HYDROGEN AND PtX IN DENMARK:

EXAMPLES FROM THE CITY OF FREDERICIA

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Jørgen Nielsen

CEO
TVIS, Denmark

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London

TVIS

sammen om varmen

Trekantområdets
Varmetransmissionsselskab I/S

TVIS

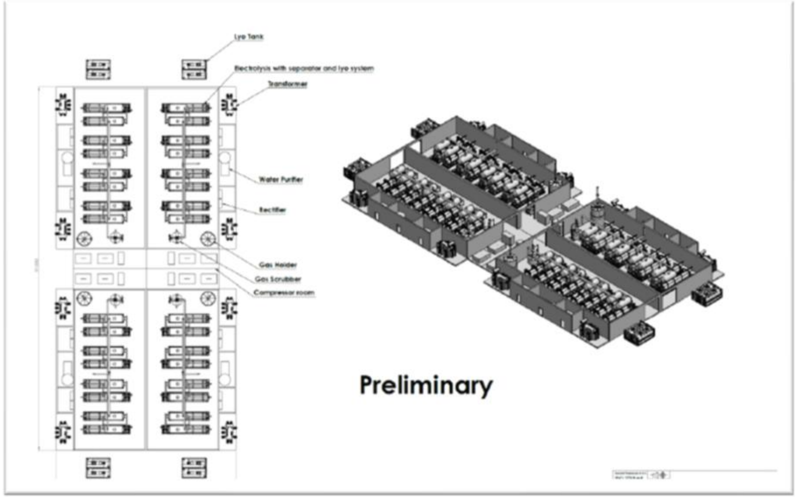
TVIS
sammen om varmen

TVIS - Operations

- 70 Stations with heat exchanger, pump stations, etc.
- 123 km main pipe trace from Vejle in the north to Kolding in the south.
- One central control room.
- Operating maximum water temperature up to 120° Celsius.
- Operating maximum hydraulically pressure up to 25 bar.
- Heat loss <2%
- Heat sale – 2.000.000 MWh/Year

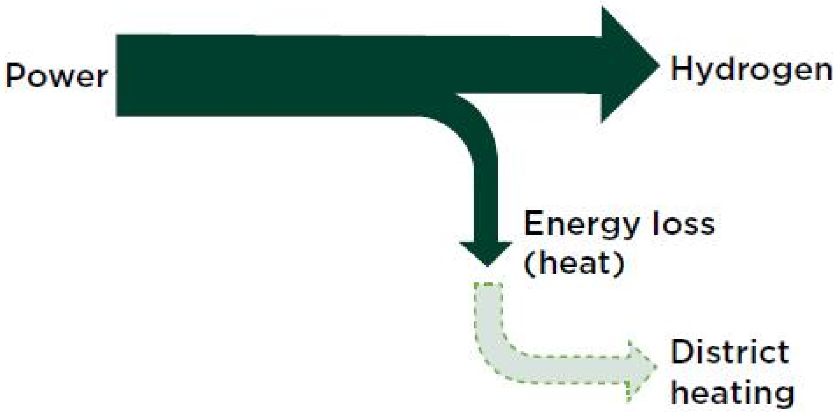
TVIS
sammen om varmen

Hydrogen



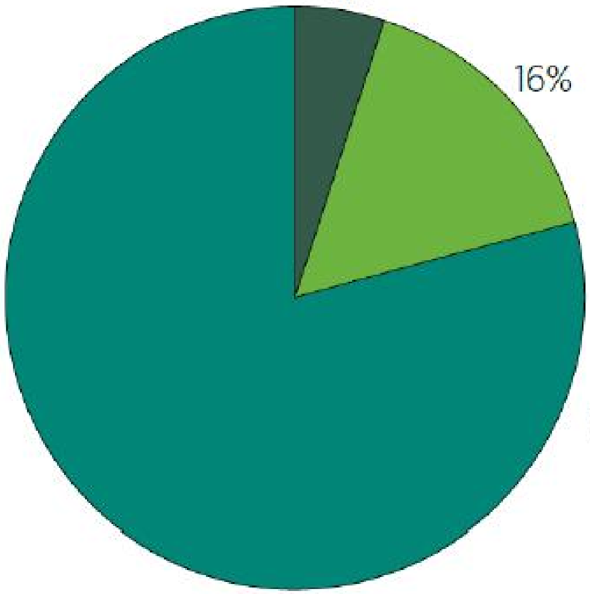
Everfuel is building a new Danish large scale hydrogen production close to the refinery (20MW).

- The ambition is to install a 3X100 MW (2024/2025).
- TVIS is one of several project partners.
- TVIS is involved in this project to help with energy storage and to bring more surplus heat into the DH-system



TVIS
sammen om varmen

Revenues – Hydrogen production.



* Not including investment in and operational costs for cooling

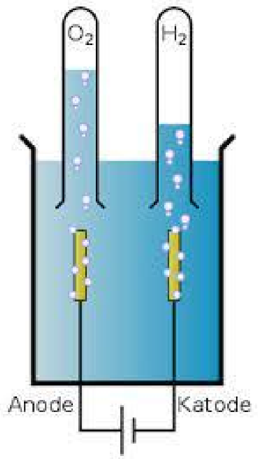
Everfuel, CBE, og TVIS –
20 MW elektrolyse i Q1 2022.

Operational hours per year: 6000
Hydrogen: 3.880 Nm3/h (ca. 350 kg/h)
Surplus heat - Direct: 10.000 MWh per year
Surplus heat – Heatpump: 18.000 MWh per year.

Oxygen: 1.940 Nm3/h (ca. 2500 kg/h)
Water: 3.880 kg/h
Waste water: 1000 kg/h

* Water: H_2O, hydrogen: H_2, Oxygen: O_2.

** 1 ton green hydrogen will reduce CO2 emissions with 10 ton at the refinery.



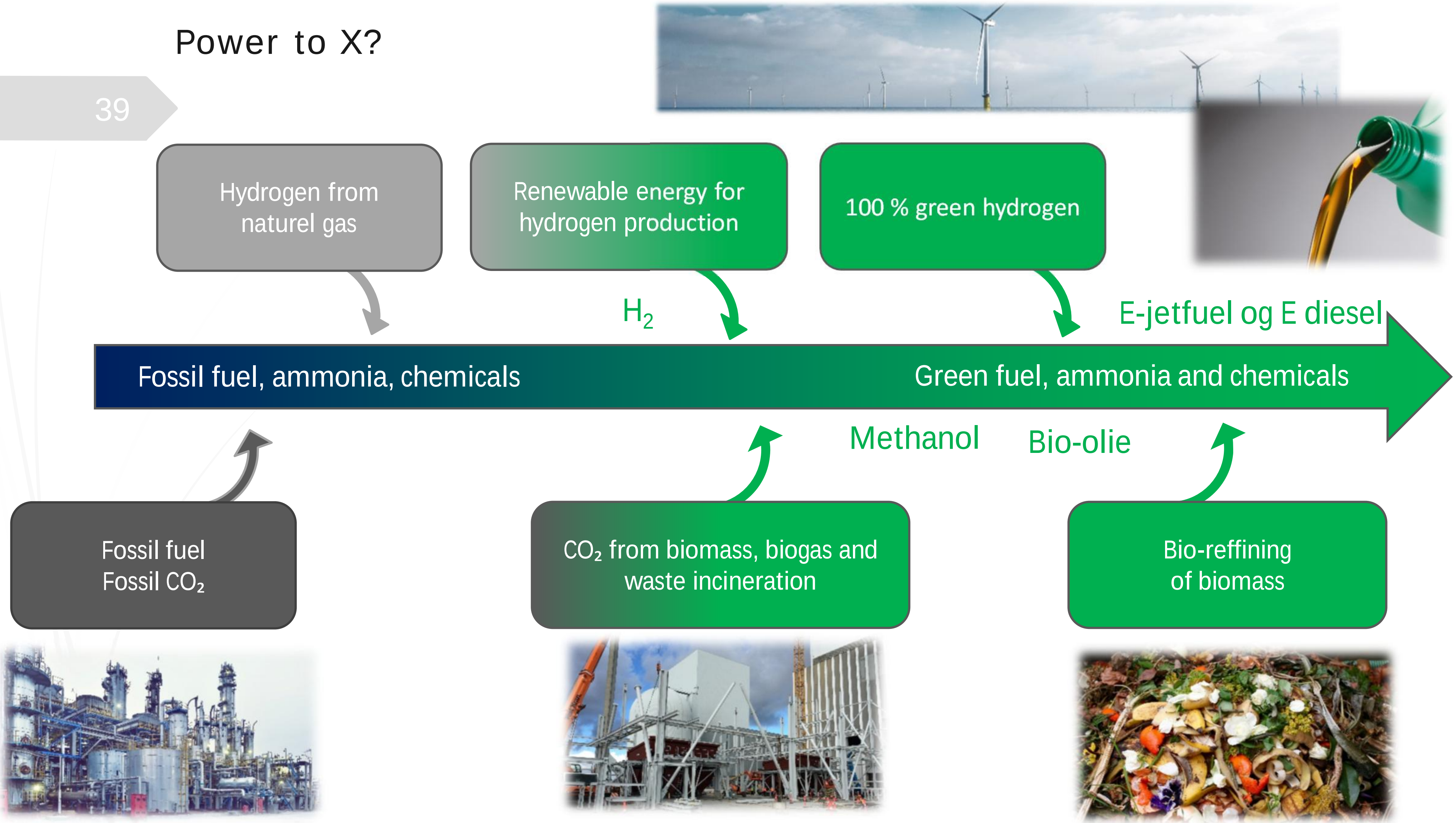
Potentialet CO2 reduction at the refinery

-123.000 ton CO2 pr år i Fredericia.

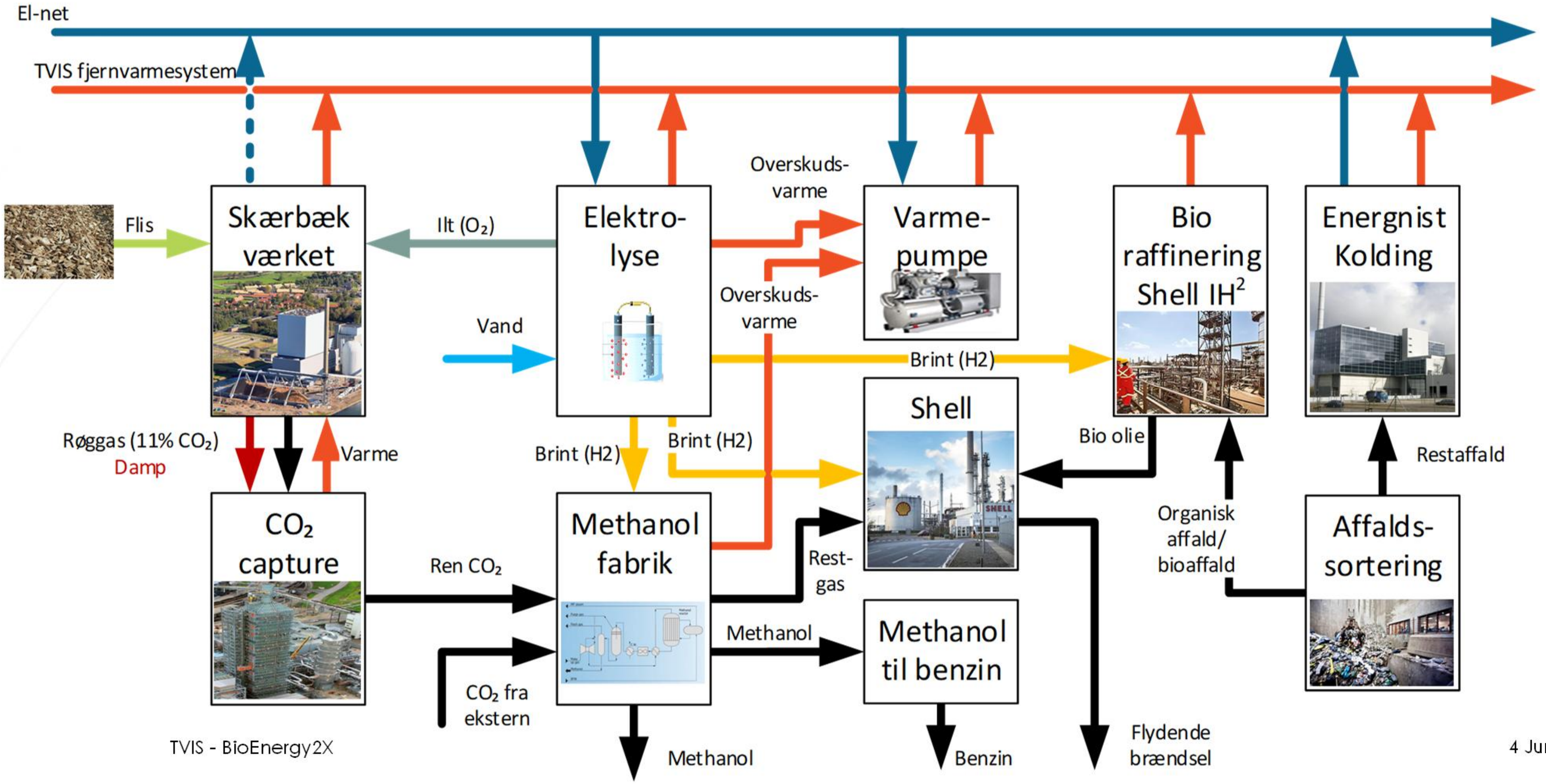
HVOR KOMMER DET FRA?	UDLEDNING AF TONS CO_2	ANDEL AF DEN TOTALE UDLEDNING
Kollektiv el- og varmeforsyning	98.000	13%
Residual-el	76.000	10%
Individuel opvarmning	4.000	<1%
Industri (gas og olie til proces)	390.000	52%
Transport	141.000	19%
Landbrug	20.000	3%
Affaldsdeponi	5.000	1%
Spildevand	1.000	<1%
Kemiske processer	9.000	1%
Total	744.000	

TVIS sammen om varmen

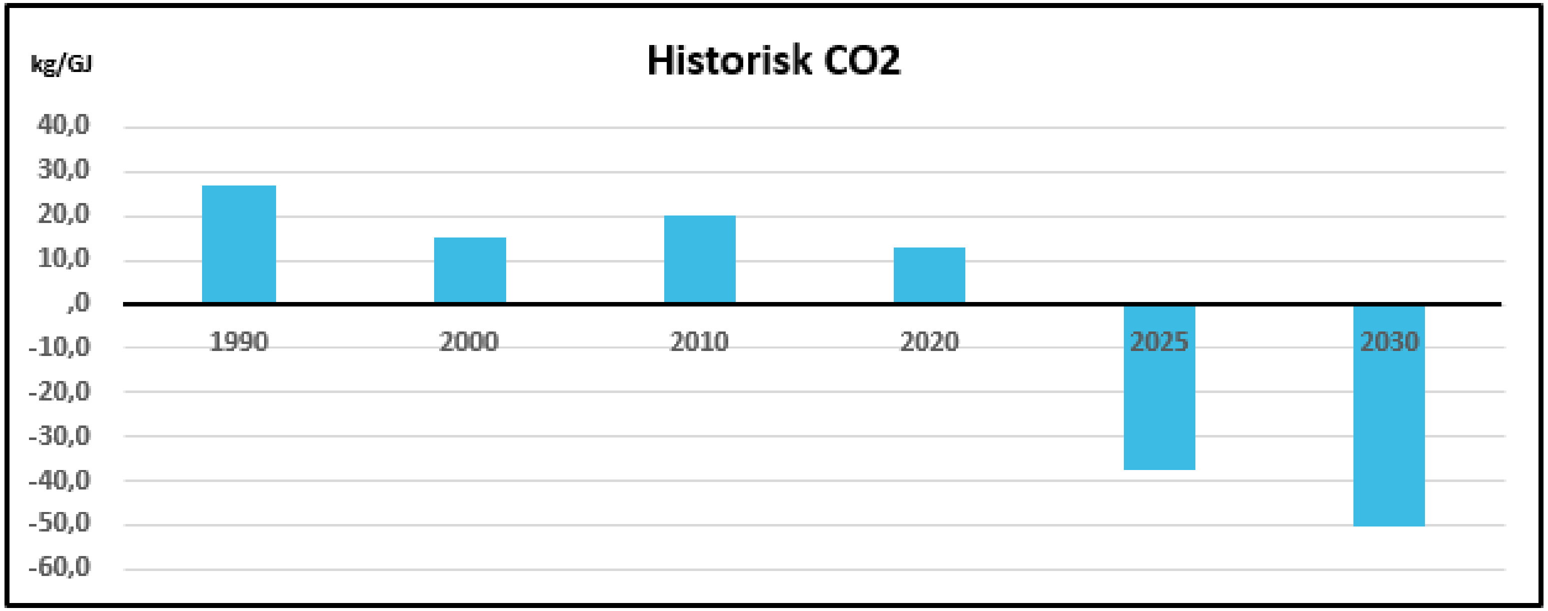
Power to X?


Hydrogen from naturel gas
Renewable energy for hydrogen production
100 % green hydrogen
H_2
E-jetfuel og E diesel
Fossil fuel, ammonia, chemicals
Green fuel, ammonia and chemicals
Methanol
Bio-olie
Fossil fuel
Fossil CO_2
CO_2 from biomass, biogas and waste incineration
Bio-reffining of biomass

Green fuels based on hydrogen, CO2 from biomass and biorefining.

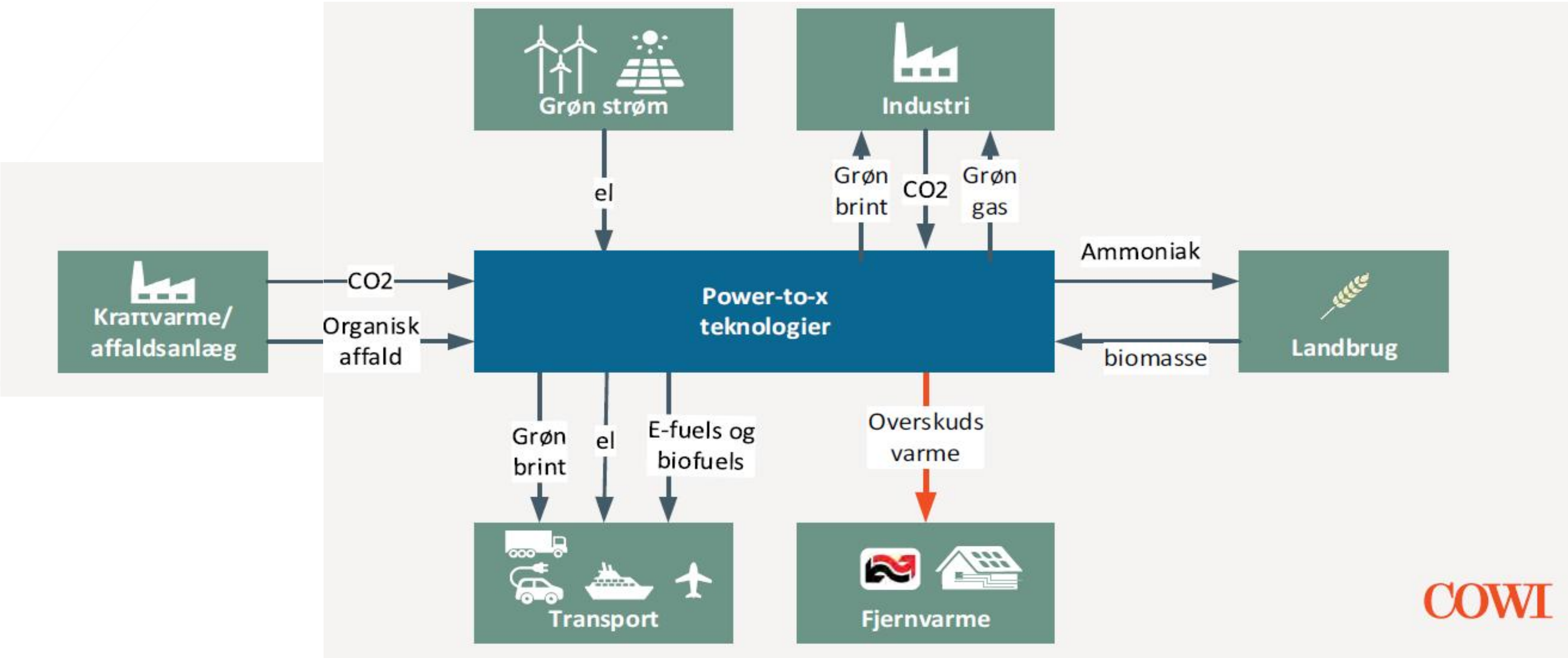


TVIS' CO2 reduction



-80.000 ton in Fredericia, -105.000 ton in Kolding,
-90.000 ton in Vejle og -25.000 ton in Middelfart.

Infrastructure is key!



Value Chain - Green fuel partnership.

Press release:

Unique cooperation will make our region a production center for green fuels.

……, we have all the prerequisites to become an international leader in Power-to-X, which is the technology where you convert green electricity into green hydrogen and green fuels… .. …..

PARTNERS (1. februar 2021)

- ☐ COWI
- ☐ Process Engineering
- ☐ Airco Process Technology A/S
- ☐ Nature Energy
- ☐ Everfuel
- ☐ Green Hydrogen
- ☐ Shell
- ☐ Ørsted
- ☐ Energnist
- ☐ Billund Lufthavn
- ☐ ADP – Fredericia Havn
- ☐ Vattenfall
- ☐ TVIS – Trekantområdets Varmetransmissionsselskab
- ☐ Trekantområdet Danmark
- ☐ Vejle Kommune
- ☐ Kolding Kommune
- ☐ Fredericia Kommune
- ☐ Middelfart Kommune
- ☐ Billund Kommune
- ☐ Haderslev Kommune
- ☐ Vejen Kommune

Thank you!

TVIS
sammen om varmen

HEAT RECOVERY PLANS
PORT OF ROTTERDAM, THE NETHERLANDS

RAMBOLL Bright ideas. Sustainable change.

EMBASSY OF DENMARK
London

Randolf Weterings

Program Manager,
Electrification and Hydrogen
Port of Rotterdam, The Netherlands

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London

HEAT RECOVERY FROM HYDROGEN PRODUCTION

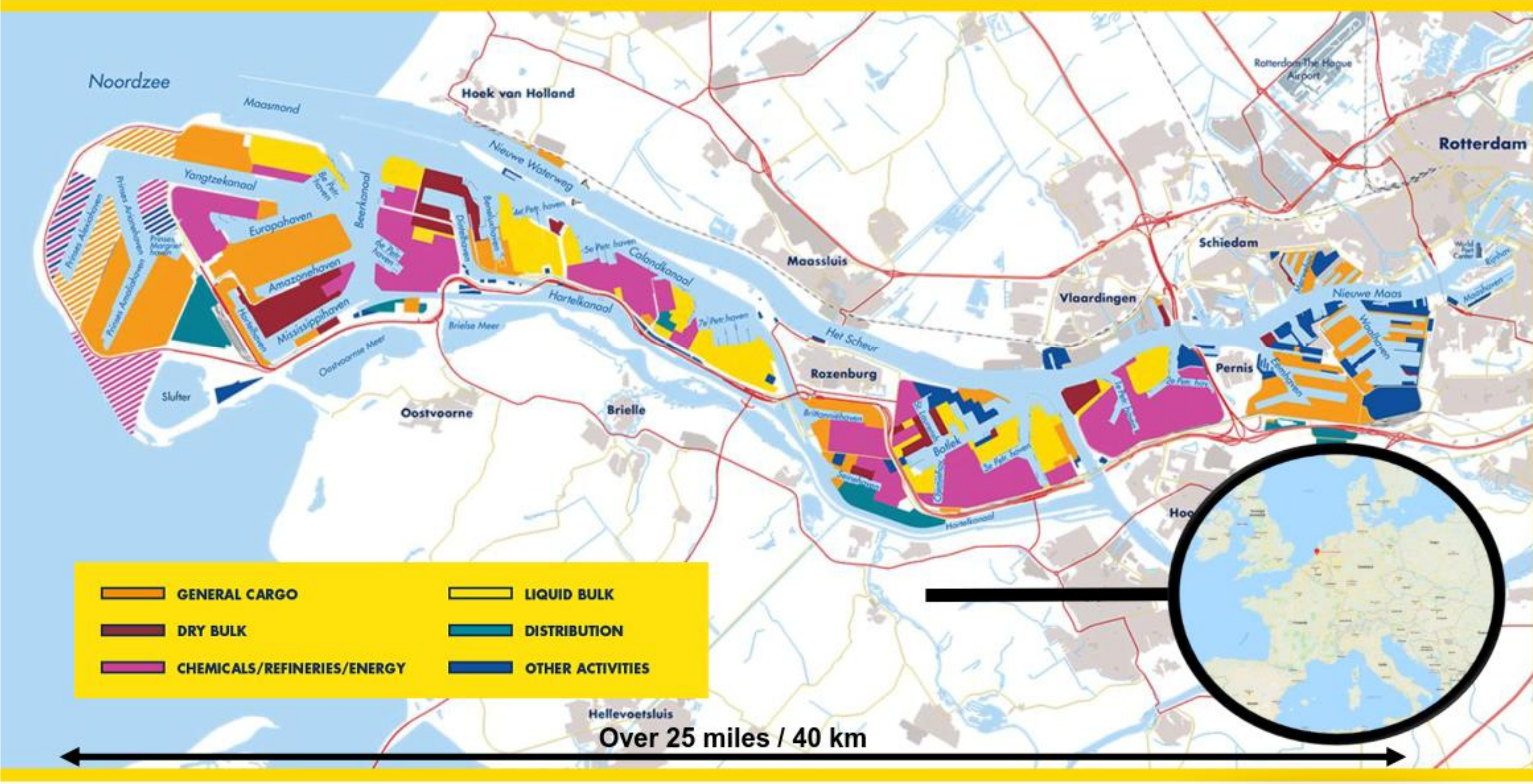
Randolf Weterings
Port of Rotterdam

Port of Rotterdam

CONTENT

- Port of Rotterdam
- Hydrogen vision & hub developments
- Conversionpark (Green Hydrogen production)
- Extract the heat for district heating and greenhouses

Port and industrial area



Port of Rotterdam

- Largest port in Europe, 10th port worldwide
- Total employment 385,000 people*
- Total added value € 45,6 billion (6.2% GNP)*
- Visits (2018):
  - 29,476 sea-going vessels
  - 107,000 inland navigation
- 3.000 companies

- Throughput (2018): 469 mln tons
  - 45% Liquid bulk
  - 32% containers
  - 17% dry bulk
  - 6% Breakbulk

** source: Erasmus University*

Port of Rotterdam

Current situation in Rotterdam

Position of Rotterdam in the current energy system (2018 figures)

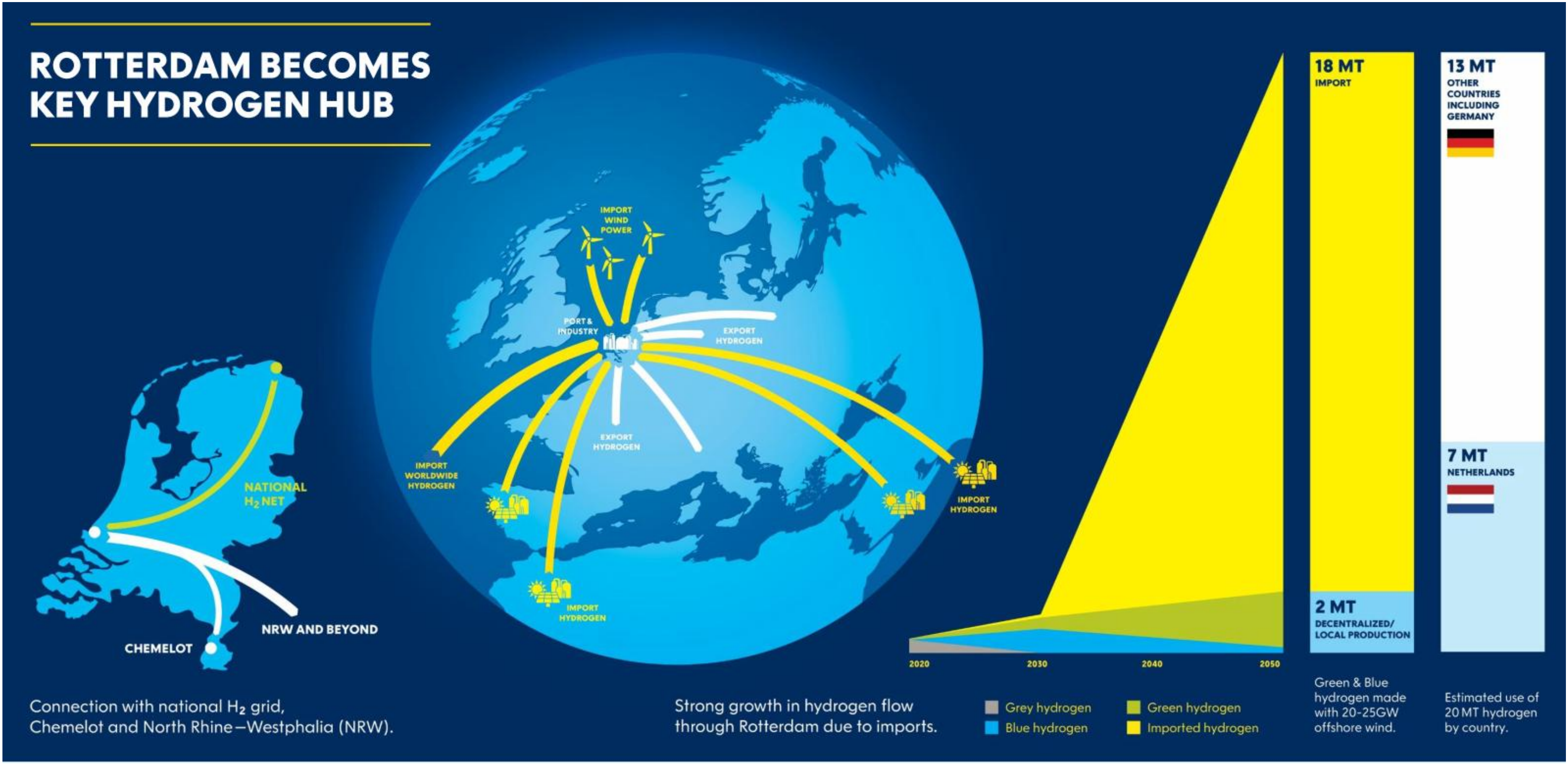
- 8.800 petajoule (PJ), 13% of the energy consumption of Europa (more than 3x the Dutch energy consumption).
- For the production of steam, heat and electricity in the Port of Rotterdam, 430PJ of energy was used (29 Mton CO2 emissions / 20% of the total Dutch emissions).

Current hydrogen market in Rotterdam

- Current hydrogen demand per year in Rotterdam is 450 kt, mainly used for oil refinery
- In the Port of Rotterdam 2 hydrogen grids exist from Air Products (local network) and Air Liquide (international network)

Pipeline network of Air Liquide, hydrogen in RED

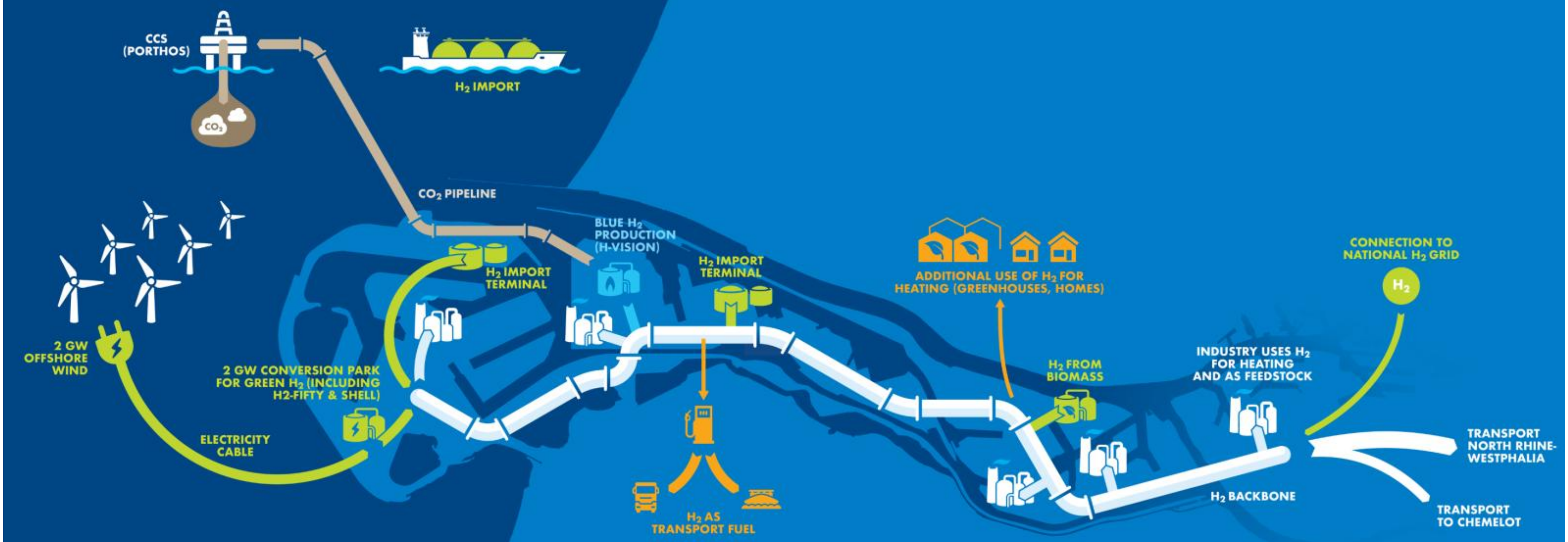
Port of Rotterdam



Hydrogen vision: https://bit.ly/32M6Wrl

Port of Rotterdam

HYDROGEN ECONOMY IN ROTTERDAM STARTS WITH OPEN ACCESS BACKBONE



The locations depicted are approximate.

Port of Rotterdam

Port of Rotterdam

EXTRACT THE HEAT FOR DISTRICT HEATING AND GREEN HOUSES

Port of Rotterdam

CO2 Pipeline

In the Porthos Project an infrastructure is being developed to store CO2 in empty natural gas field in the North Sea. The CO2 originates from the industry in the port and possibly for abroad in the future. Start of construction is planned in 2022 an the start of operation is planned in 2024.

Suppliers and offtakers

The main suppliers of the CO2 are the chemical industry and the refineries. The first offtakers are greenhouses. Storage is planned in empty an empty gas field of TAQA under the North Sea, which has a capacity of 37 Mton CO2. It is expected that a CO2 network will attract new companies and stimulate the use of CO2 as a feedstock (for synthetic fuels for example)

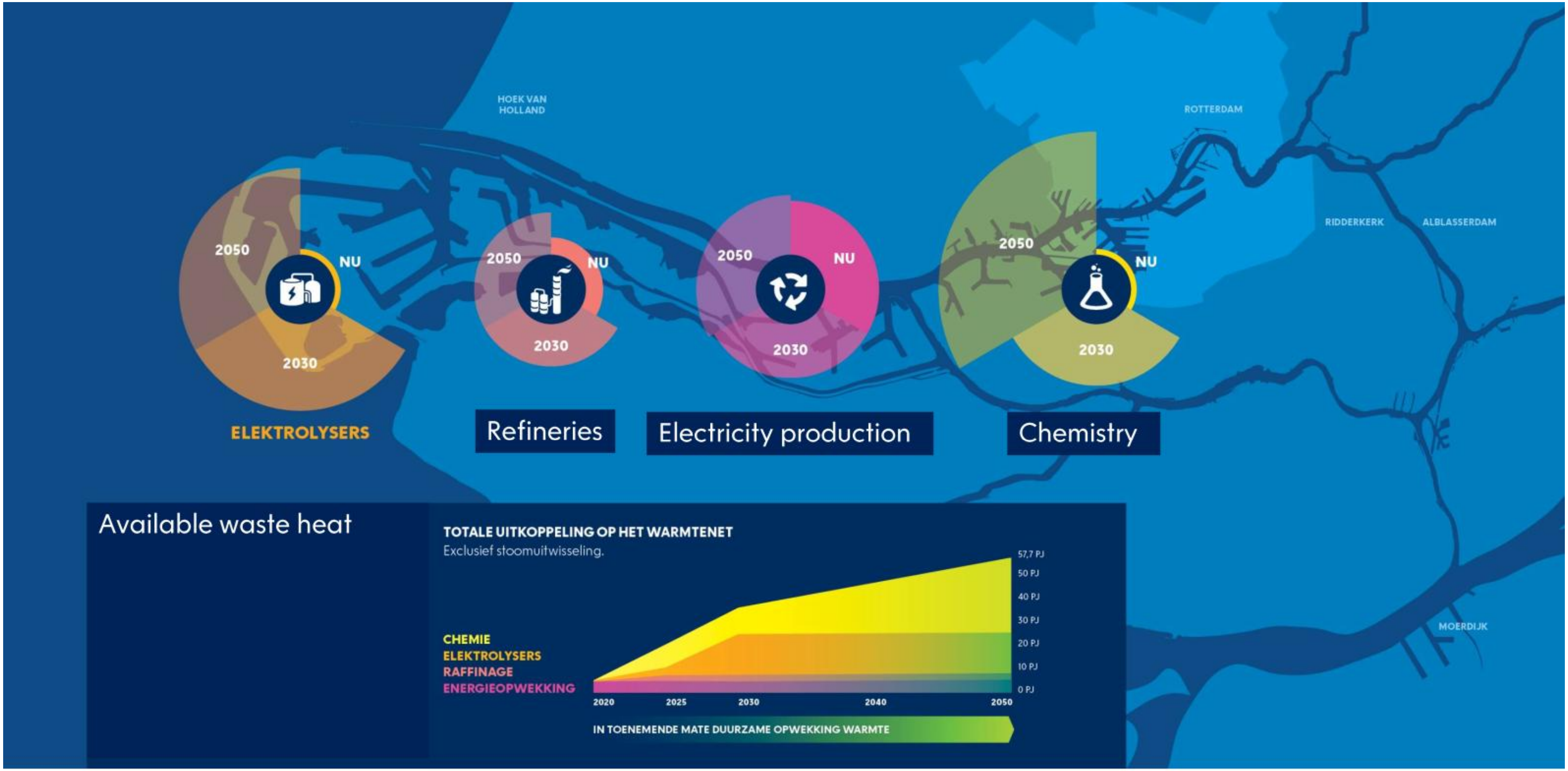
Expected CO2 reduction in 2030

+- 3-13 Mton per year

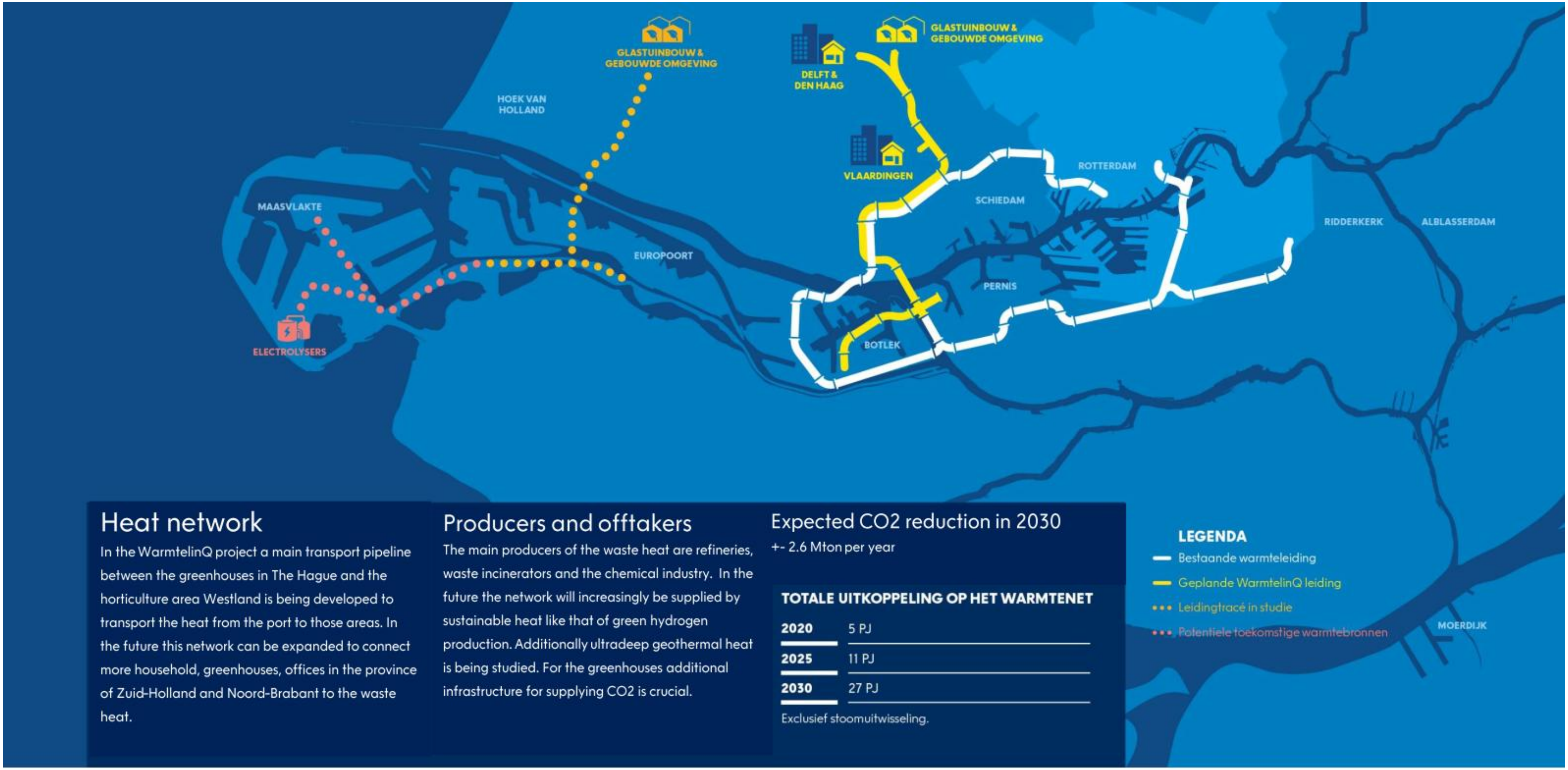
TOTALE UITKOPPELING

2020	0,6 MT PER JAAR
2025	3,0 MT PER JAAR
2030	9,0 MT PER JAAR

Port of Rotterdam



Port of Rotterdam



Heat network

In the WarmtelinQ project a main transport pipeline between the greenhouses in The Hague and the horticulture area Westland is being developed to transport the heat from the port to those areas. In the future this network can be expanded to connect more household, greenhouses, offices in the province of Zuid-Holland and Noord-Brabant to the waste heat.

Producers and offtakers

The main producers of the waste heat are refineries, waste incinerators and the chemical industry. In the future the network will increasingly be supplied by sustainable heat like that of green hydrogen production. Additionally ultradeep geothermal heat is being studied. For the greenhouses additional infrastructure for supplying CO2 is crucial.

Expected CO2 reduction in 2030

+- 2.6 Mton per year

TOTALE UITKOPPELING OP HET WARMTENET

2020	5 PJ
2025	11 PJ
2030	27 PJ

Exclusief stoomuitwisseling.

Port of Rotterdam

POWER UP YOUR IDEAS
MAKE IT HAPPEN

Randolf Weterings

LET'S CONNECT

Port of Rotterdam

DISCUSSION / QUESTIONS

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Break
10 minutes

SYNERGY STUDY OF HEAT RECOVERY FROM HYDROGEN PRODUCTION IN THE UK

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London

Synergy Study Project Team

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Hydrogen

Dan King
Hydrogen

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Heat / Hydrogen

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Heat

Lisa Pardini
Heat

Aimilios Spinoulas
Heat

Study Background and Objectives

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STUDY BACKGROUND

- Hydrogen is expected to play a key role in meeting Net Zero, both in the UK and beyond.
- A lesser known fact is that hydrogen production – be that blue or green hydrogen – will result in substantial amounts of energy being lost as heat.
- This presents an opportunity for both:
  - The Hydrogen Sector - to increase energy efficiency and revenue; and,
  - The District Energy sector – to capitalise on what otherwise would be vented to the atmosphere.
- In March 2021, Ramboll Energy was appointed by the Danish Embassy to assess the potential synergies between future hydrogen production and associated heat recovery for the use in district heating.
- Building on inspiration from Europe, in particular Denmark, the Study has focussed on the UK due its ambitions timescale for hydrogen production as well as district heating network (DHN) development and deployment.

STUDY OBJECTIVES

Review existing and proposed hydrogen and district heat network projects to:

- *Create a Vision and Associated Narrative for Heat Recovery from Hydrogen Production*

  Noting the likely development of hydrogen / industrial clusters, the Study will provide local policy makers with a vision and narrative for engaging in sustainable heat planning.

- *Highlight Potential Investment Opportunities for both Hydrogen and District Heating Network Investors*

  The Study will highlight the immediate and potential future applications and opportunities.

- *Re-Capture and Solidify Wider Interest in Waste Heat Recovery*

  Noting the political attention currently granted to hydrogen, the Study is a novel way to re-capture and / or solidify wider interest in waste heat recovery from industry, whilst also commenting on the possible policy barriers and driver that exist.

The Results of the Study will also be of interest to Policy Makers and Hydrogen and Heat Network Investors outside the UK

Technical Information / Recap

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WASTE HEAT POTENTIAL FROM HYDROGEN PRODUCTION

- *In Green Hydrogen production:*

  Hydrogen is produced using electricity in an electrolyser to split water (H_2O) molecules to produce hydrogen (H_2) and oxygen (O_2).

  The electricity supplied to the electrolyser is more than the energy required for the splitting reaction. Therefore, waste heat is generated.

  Depending on the design / type of electrolyser, waste heat generated represents between 17 to 25% of the total input energy, at temperatures between 40°C to 77°C.

- *In Blue Hydrogen production:*

  Hydrogen is produced via a steam-methane reforming process, which mixes steam (H_2O) with methane (CH_4) to (ultimately) produce hydrogen (H_2) and carbon dioxide (CO_2). For blue hydrogen production, this process is coupled with CO_2 capture and storage to produce low-carbon hydrogen.

  Whilst the core process is already optimised, there may be good potential for waste heat recovery from the CO_2 capture auxiliary processes, such as cooling and compression.

  Such waste heat recovery needs further assessment on a project-to-project basis, and initial estimates of the waste heat generated and associated temperatures are highly variable.

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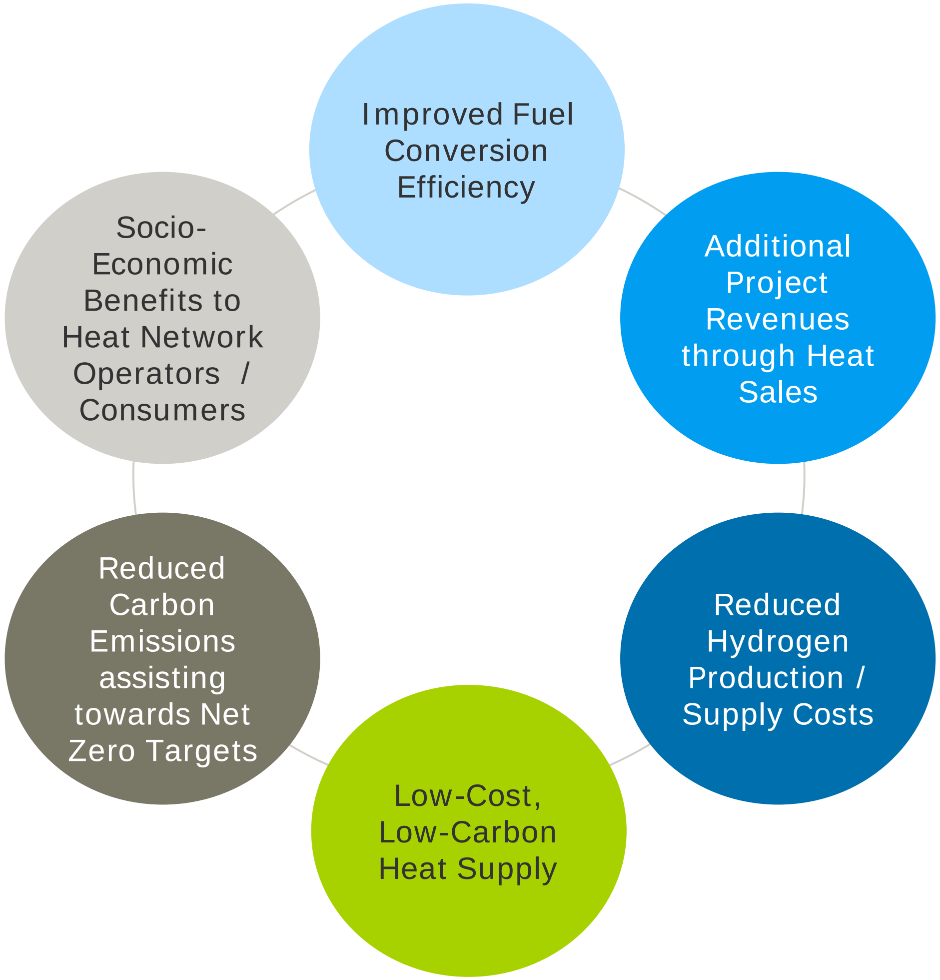
BENEFITS OF WASTE HEAT RECOVERY



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Synergy Identification / Recap

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SYNERGIES SUMMARY

- Three Synergy Locations were considered:
  Humber Region; Aberdeen City Centre; and, Leeds City Centre.
- For each Location:
  - The potential waste heat from hydrogen production was determined; and,
  - A heat demand and supply peak analysis was undertaken.
- Humber Region shows great hydrogen production potential with solid plans for DHN in the coming years, while also having large offshore wind farms which could increase the hydrogen production potential.
- Aberdeen has a good balance of hydrogen production potential with an existing DHN, while also having large offshore wind farms which could increase the hydrogen production potential.
- Leeds currently has limited hydrogen production potential, but does have a large existing DHN with aims to extend further in the coming years.

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SYNERGIES SUMMARY

Synergy Location	Existing / Committed District Heating Demand (MW)	Proposed District Heating Demand (MW)	Estimated City-wide Heat Demand (MW)	Potential Waste Heat from Hydrogen (MW)	Potential Waste Heat from (Offshore Wind) Hydrogen (MW)
South Humber	0	42	125	219	31
Hull	10	10	350	175	5
Beverley	0	5	20	11	30
Aberdeen City Centre	11	20	210	2.0	13
Leeds City Centre	22	150	300	1	-

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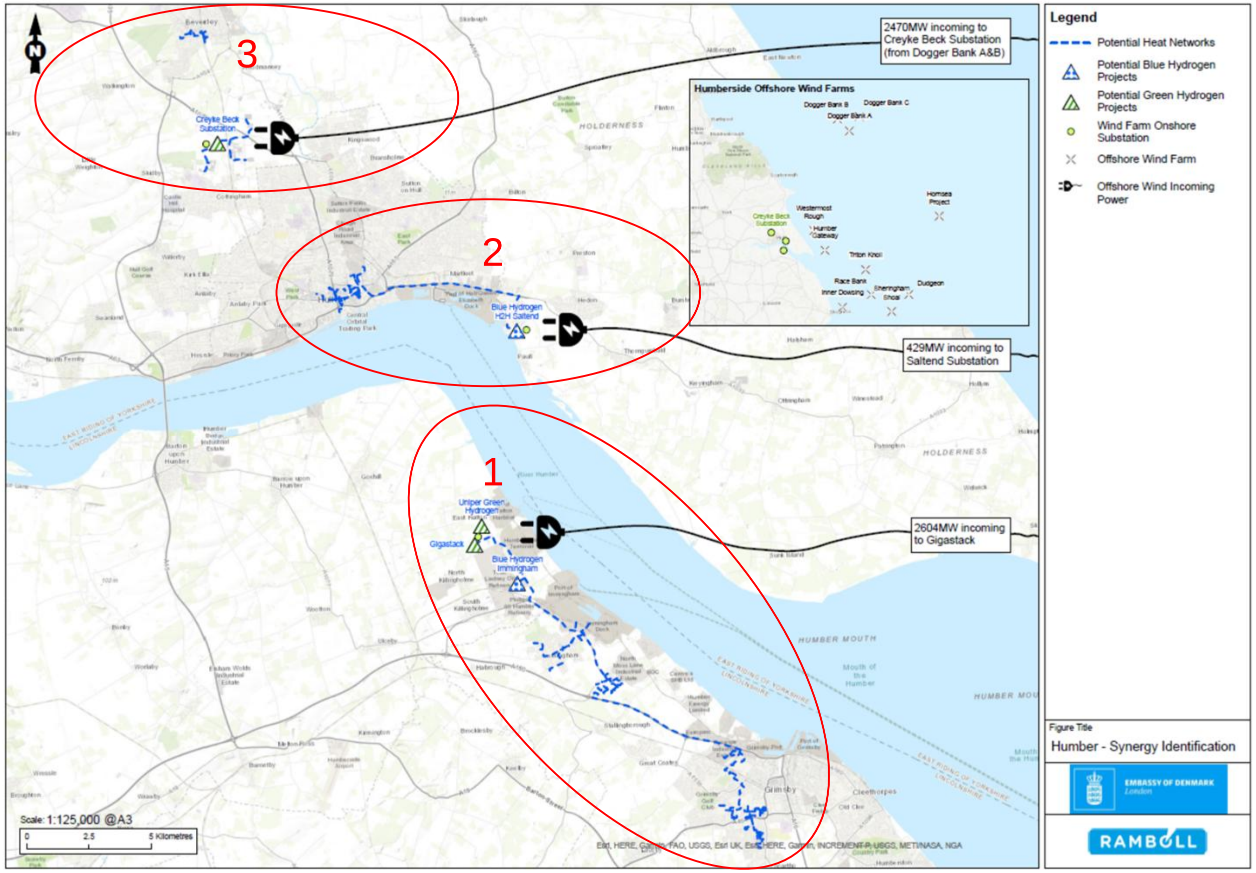
HUMBER REGION MAPPING



Three Synergies identified in the Humber Region:

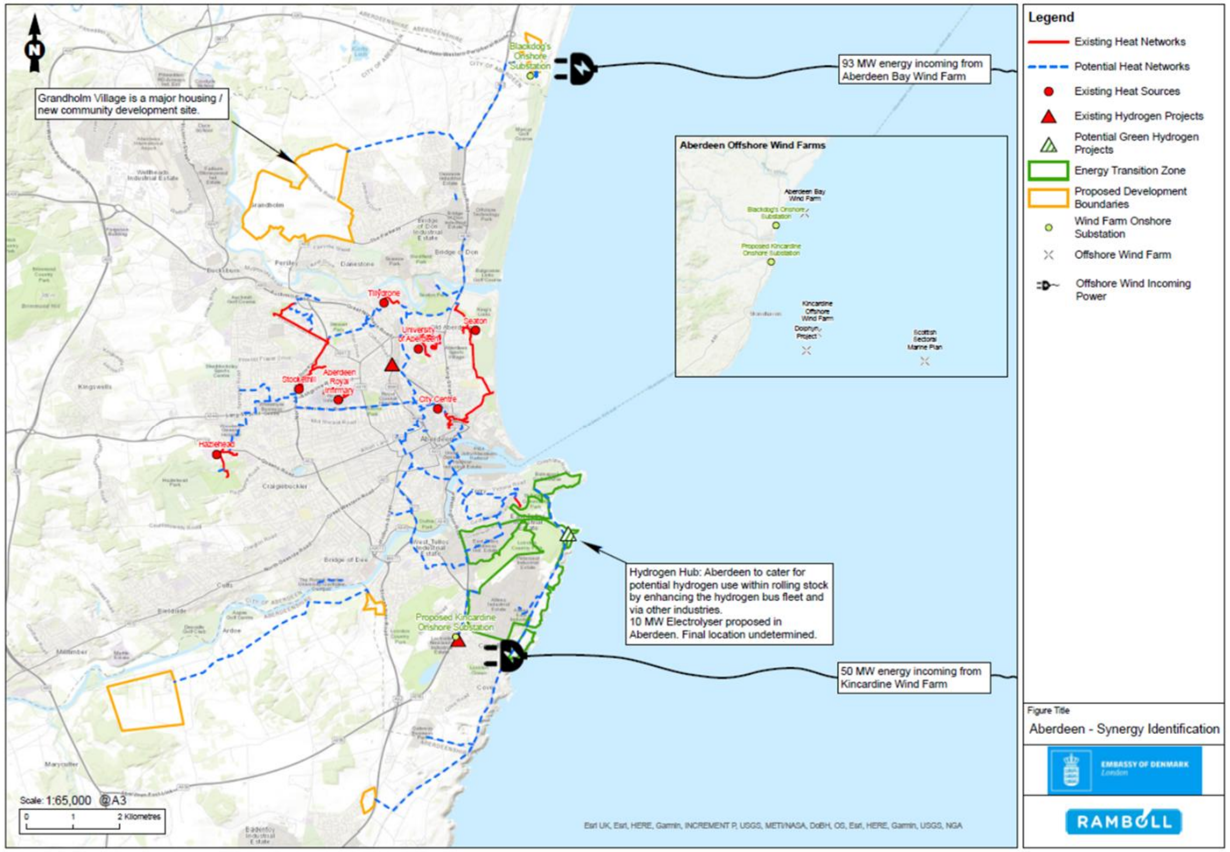
1) South Humber –
   Five proposed Heat Clusters
   which could receive Heat from
   Giga Stack and Uniper Hydrogen
   production facilities

2) Hull
   Town centre DHN
   which could receive Heat from
   H2H Saltend Hydrogen production facility

3) Beverley
   Proposed DHN in the area along with Greenhouses
   which could receive Heat from
   Equinor Hydrogen production facility

In addition, a number of offshore wind turbines are already commissioned or currently under construction. These will generate renewable electricity which could also be utilised for Hydrogen production.

ABERDEEN MAPPING

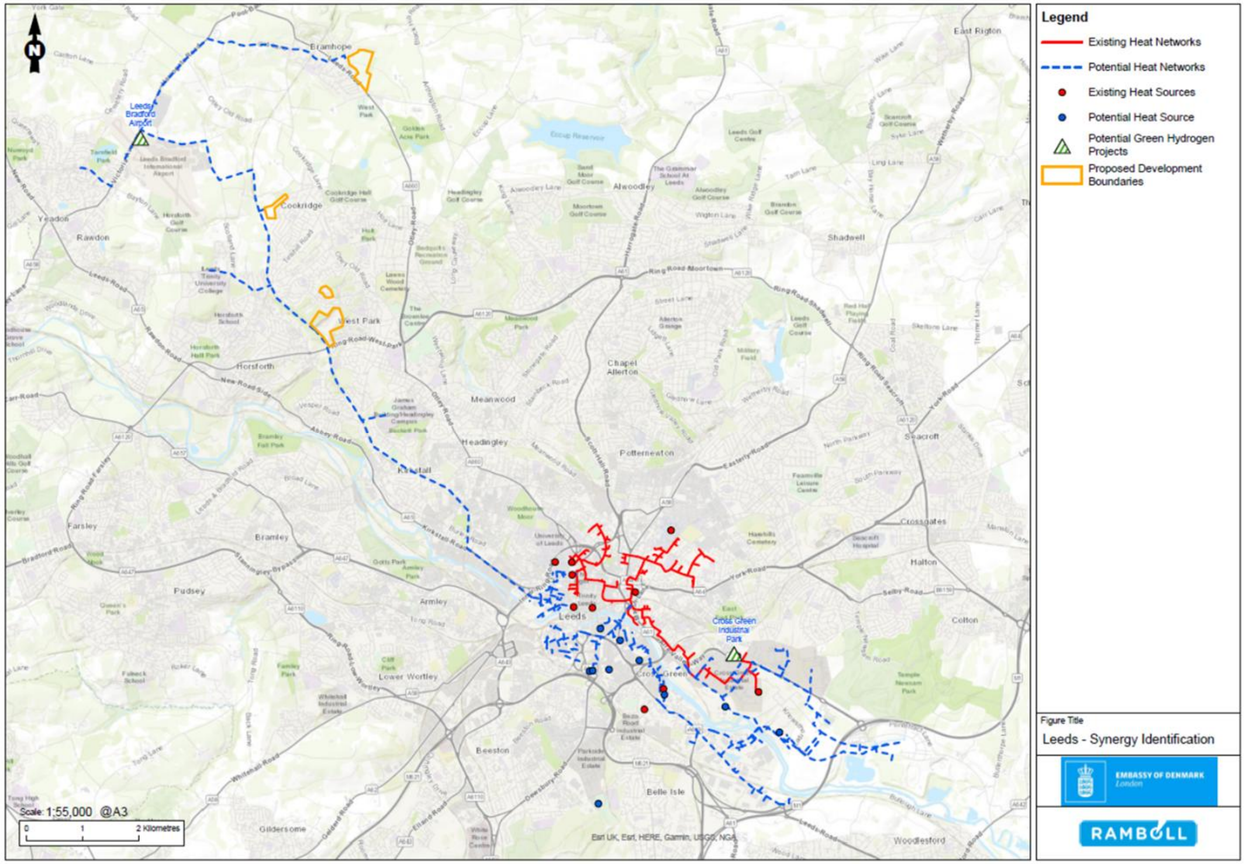


Aberdeen has a number of existing DHN across the city and aims to build a city wide heat network.

Through the H2 Aberdeen programme, Aberdeen is also on the forefront of Hydrogen production to create a hydrogen economy in the region.

In addition, a number of offshore wind turbines are already commissioned or currently under construction. These will generate renewable electricity which could also be utilised for Hydrogen production.

LEEDS MAPPING



Leeds has a large existing DHN, with ambition to extend capacity up to 150MW in the coming years.

Currently plans for Hydrogen production are very limited in the area with only Leeds Bradford Airport and Leeds Waste and Recycling Centre projects under consideration.

Definitely an area where Hydrogen production could be investigated further. However the current heat sources may limit the need for additional sources of heat (e.g. waste heat from Hydrogen production).

Technical Appraisal

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TECHNICAL APPRAISAL RESULTS

	South Humber	Hull	Beverley	Aberdeen City Centre	Leeds City Centre
H_2 Heat Availability (Max)	5	5	4	3	1
Heat Demand (Max)	4	4	3	5	5
Distance	4	3	3	4	4
Heat Quality (Temp)	2	2	2	2	2
H_2 Growth Potential	5	5	4	5	2
DHN Growth Potential	4	4	2	5	5
Level of Stakeholder Interest	4	4	2	4	2
Timescale to Implementation	4	4	2	5	1
Transferability	5	3	4	4	4
Scoring	4.10	3.80	3.00	3.95	3.00

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SELECTED SYNERGY – SOUTH HUMBER

- South Humber has been selected as it has several large hydrogen production projects under development, and existing plans for several DHN in the area.
- There are two 100MW Green Hydrogen production projects, one of which is in the FEED phase.
- There is also a 700MW Blue Hydrogen production project.
- Local authorities have commissioned a feasibility study for a number of DHN, with a heat demand of 42 MW and a potential city wide demand of 125 MW.
- The potential heating networks are in pockets moving outwards from the hydrogen production facilities which offers a potential phased development opportunity.
- The analysis of this Synergy would have a potential benefit to all stakeholders within the other areas investigated as the analysis data can be adjusted to suit the different options available.

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NOTE ON

WIDER APPLICABILITY / TRANSFERABILITY

- The South Humber Synergy has both Green Hydrogen and Blue Hydrogen production.
- As previously noted, waste heat potential is apparent in both production processes, and both production processes play an important role in the future Hydrogen economy.
- A large facility with scaled hydrogen and DHN growth potential would benefit more projects and translate to a good case to provide an element of transferable and interchangeable data.
- Alternative cases are also able to benefit from this synergy by subtracting unnecessary elements (for example existing DHN vs new DHN).

- Therefore, exploration of this Synergy has the potential to benefit all other Synergies.

High-Level Economic Appraisal

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METHODOLOGY

01 Hydrogen Project Scenario

- H_2 Project
- Capacity Factor
- Waste Heat Availability
- Waste Heat Temperature

02 Counterfactual Scenario

- Alternative Low / Zero Carbon Heat Source

03 Initial Technical Assessment

- Heat Demand
- DHN Temperature
- DHN Route / Sizing
- Heat Supply Strategy
- Energy Centre Location / Sizing

04 Techno-Economic Assessment

- CAPEX / OPEX / REPEX
- Revenues and Cash Flows
- Carbon Assessment
- Cost of Heat
- NPV, IRR, ROI

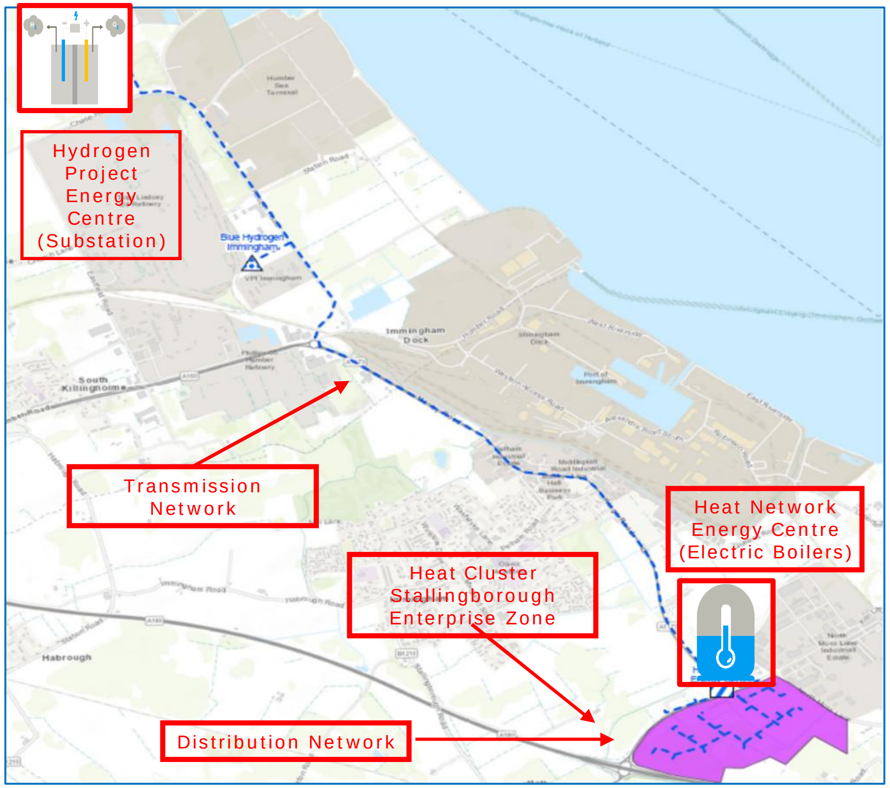
05 Sensitivity Assessment

- Capacity Factor
- Waste Heat Availability
- Waste Heat Temperature
- Heat Demand
- DHN Temperature
- DHN Length
- CAPEX
- Heat Sale Rate
- Grant Funding

06 Impact Assessment

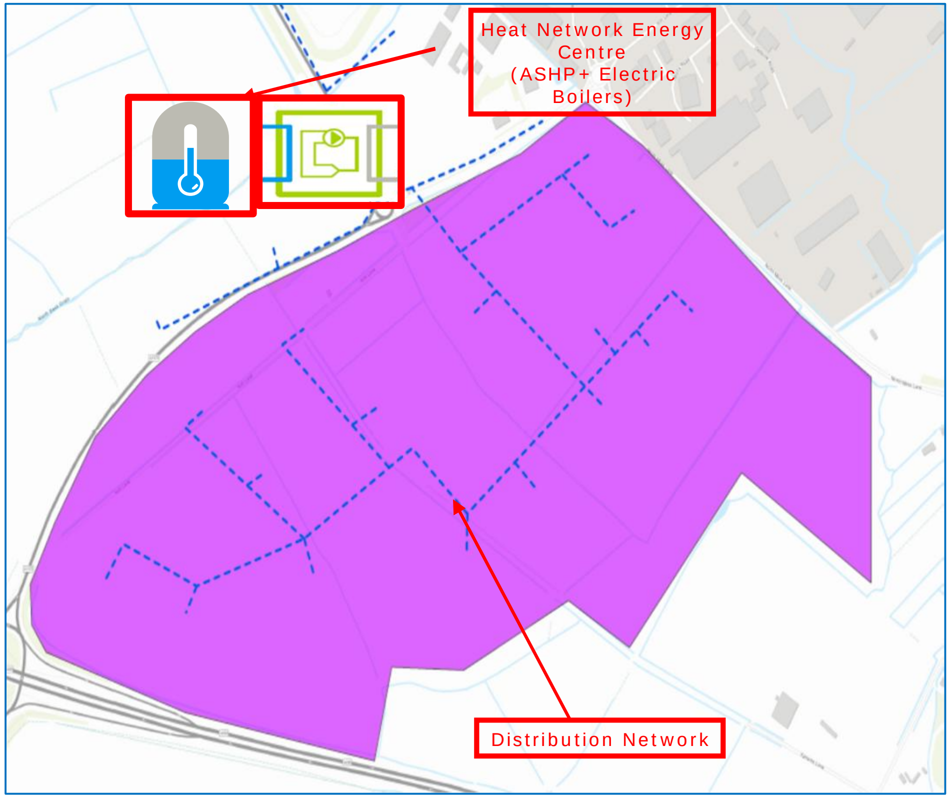
- Impact on H_2 Projects
- Impact on DHN Projects
- Impact on Consumers
- Key Enablers and Blockers

MODELLING SCENARIOS



Project Scenario:

Primary Heat Source: Green Hydrogen Waste Heat
Secondary Heat Source (Backup / Peak Load): Electric Boilers



Counterfactual Scenario:

Primary Heat Source: Air Source Heat Pumps
Secondary Heat Source (Backup / Peak Load): Electric Boilers

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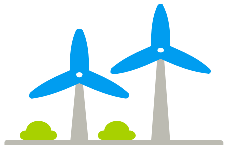
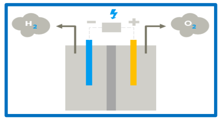
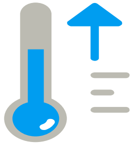
HYDROGEN PROJECT SCENARIO

- Heat Cluster: Stallingborough Enterprise Zone

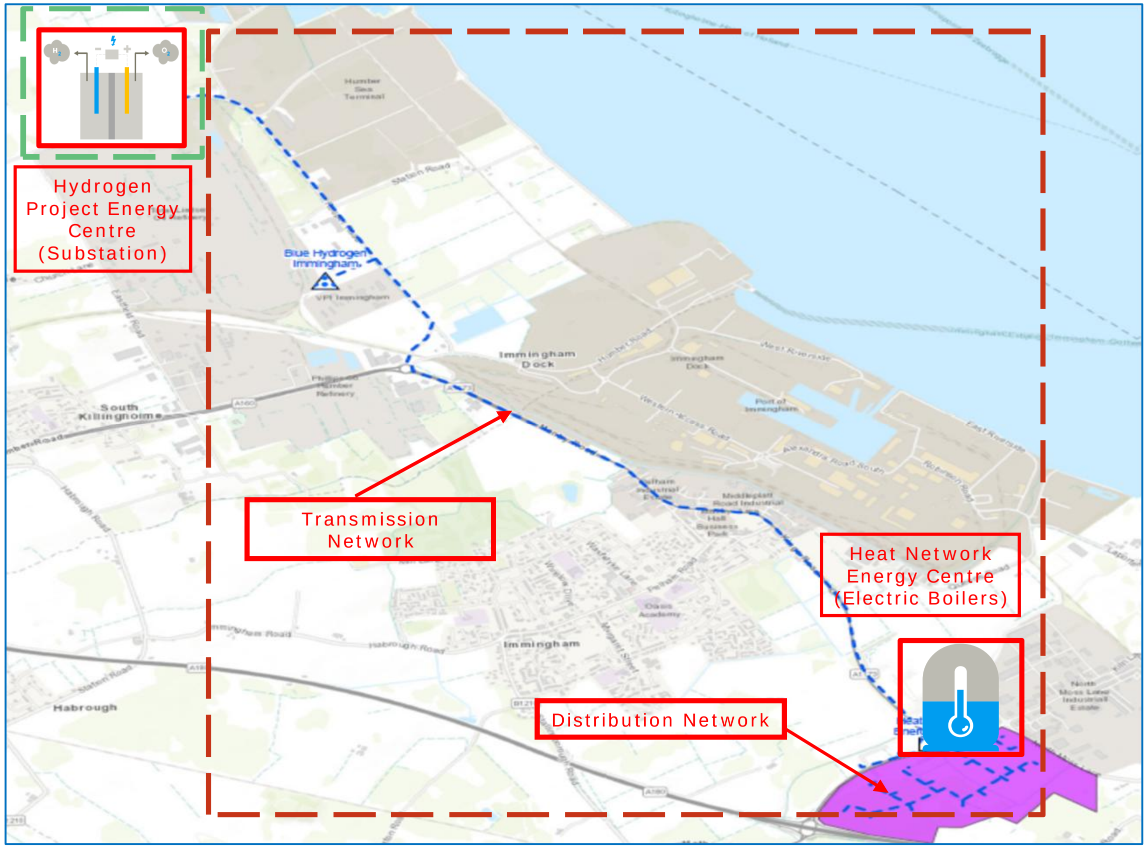
- Hydrogen Production Capacity
  - Green Hydrogen (Gigastack or Uniper Green)
  - 20 MW
- Waste Heat Available
  - Peak: 4.4 MW
  - Average: 2.64 MW (60% Capacity factor)
- Heat Demand
  - Peak: 15 MW
  - Annual: 24.6 GWh
- Heat Supply
  - Hydrogen Waste Heat: 75%
  - Electric Boilers: 25%
- Operating Temperature
  - Waste Heat supply: 80 / 50°C
  - Heat Network: 70 / 40°C







PROJECT SCENARIO: SCOPE SPLIT AND ASSUMPTIONS



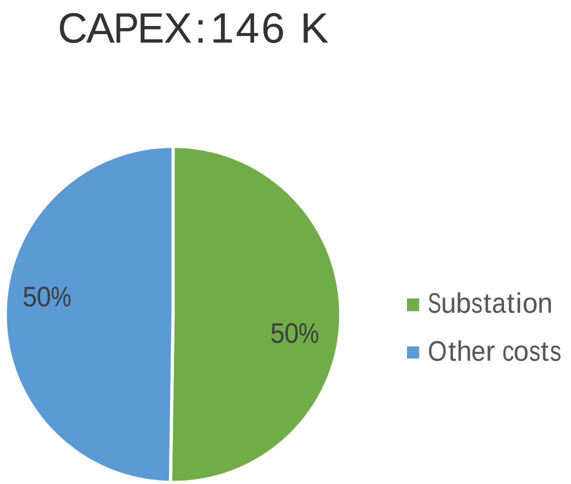
Hydrogen Project Scope

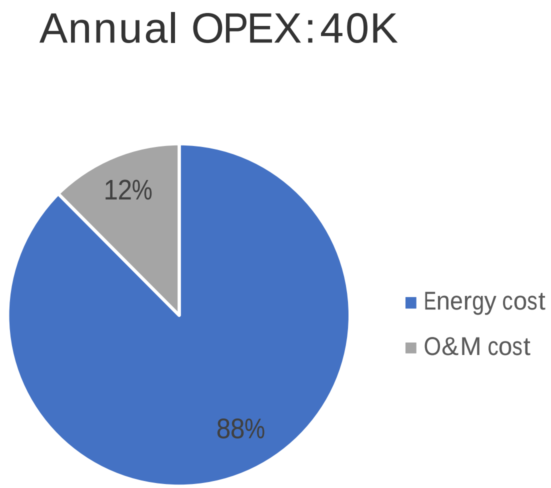
Heat Network Project Scope

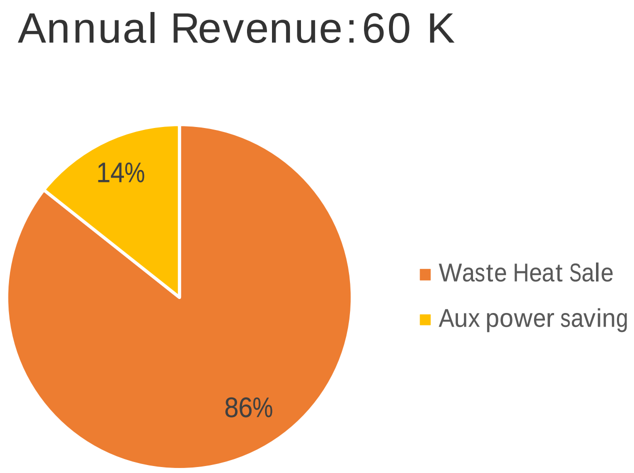
- Other Assumptions:
  - Project Life Cycle: 40 Years
  - Discount Rate: 3.5%
  - Heat Sale Rate: Levelised Cost +10%
    - H2 Project to DHN: 2.7 £/MWh
    - DHN to Consumers: 83.7 £/MWh

RAMBOLL

RESULTS: IMPACT ON HYDROGEN PROJECT







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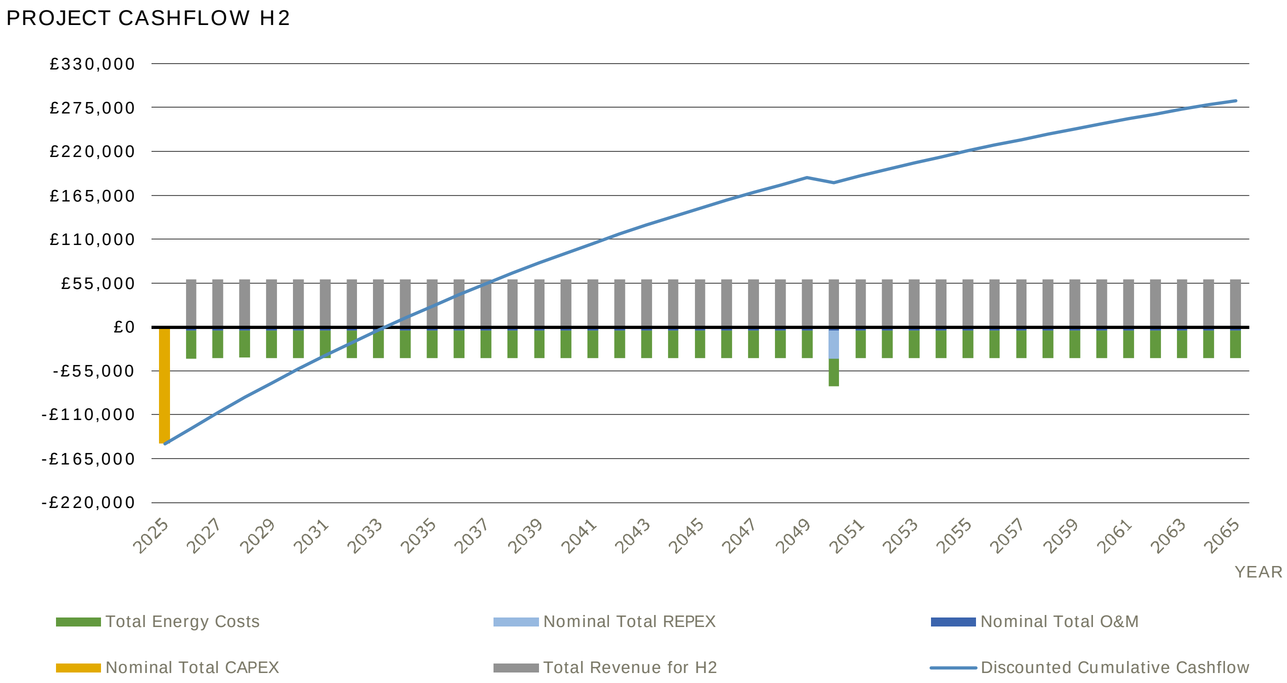
IMPACT ON HYDROGEN PROJECT: JUSTIFIED BUSINESS CASE

➢ Key Financial Results

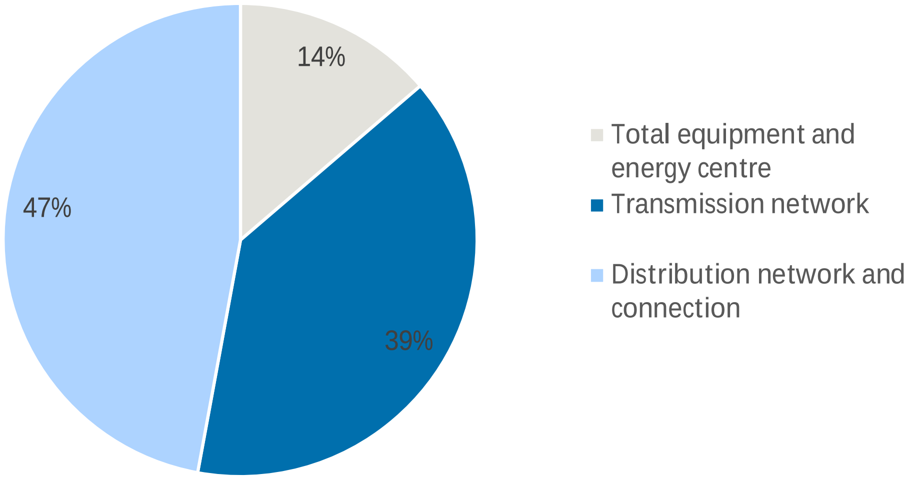
Parameter	Unit	Results
IRR (40 years)	%	14
NPV (40 years)	k£	284
Levelised Cost	£/MWh	2.51



RAMBOLL

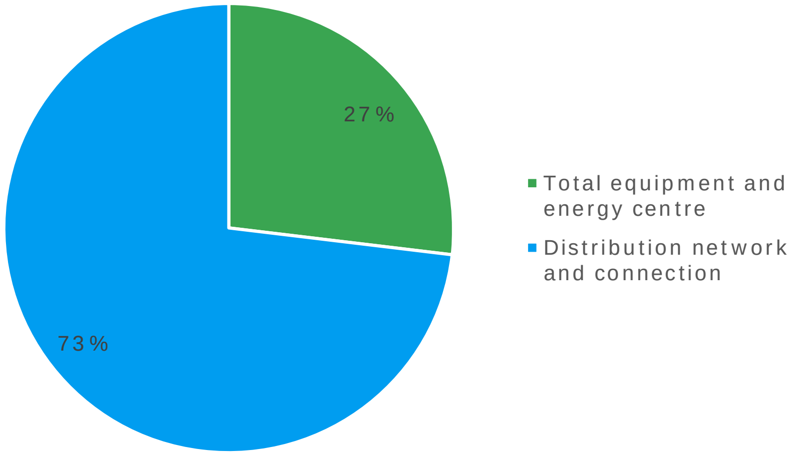
RESULTS: IMPACT ON HEAT NETWORK

CAPEX: £17.4 m



Synergy Project Scenario

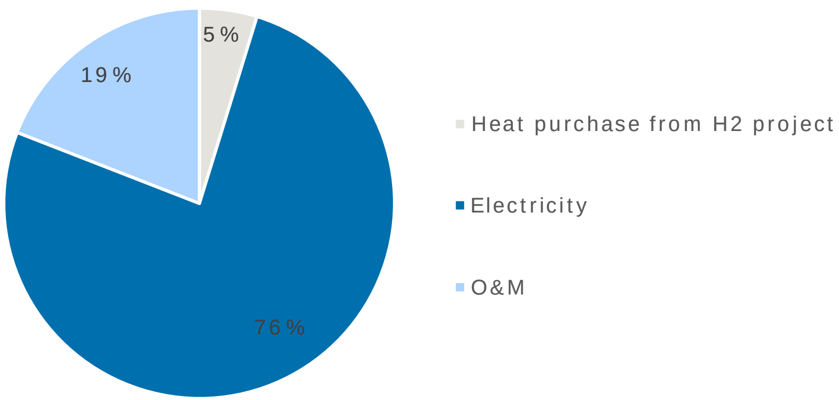
CAPEX: £11.2 m



Counterfactual Scenario

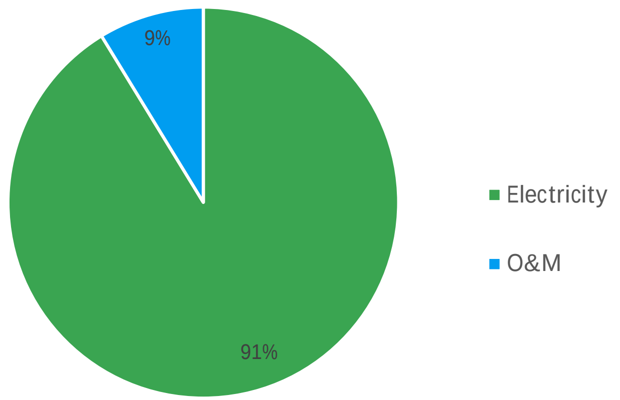
RESULTS: IMPACT ON HEAT NETWORK

Annual OPEX: £0.8 m



Synergy Project Scenario

Annual OPEX: £1.7 m



Counterfactual Scenario

IMPACT ON DHN PROJECT: JUSTIFIED BUSINESS CASE

- Key Financial Results

Parameter	Unit	Synergy	Counterfactual
IRR (40 years)	%	4.9	0.2
NPV (40 years)	m£	4	-4.8
Levelised Cost	£/MWh	75.9	92.9

- Cost to the users

Parameter	Unit	Synergy	Counterfactual
Cost of Heat	£/MWh	83.7	102.2*

*The cost is LCOE+10%. £83.7/MWh is used for modelling both the scenarios

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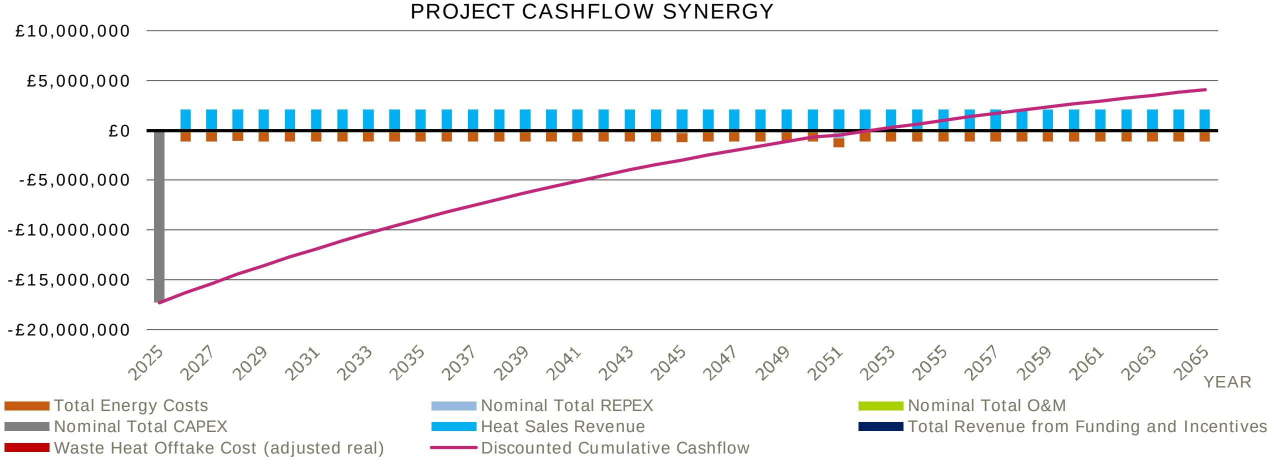
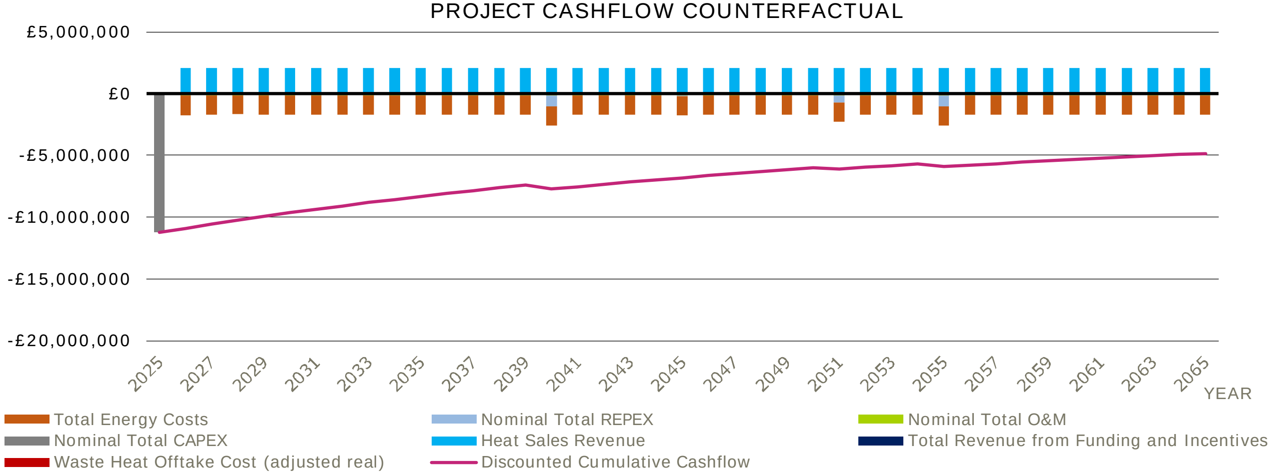
IMPACT ON DHN PROJECT: JUSTIFIED BUSINESS CASE





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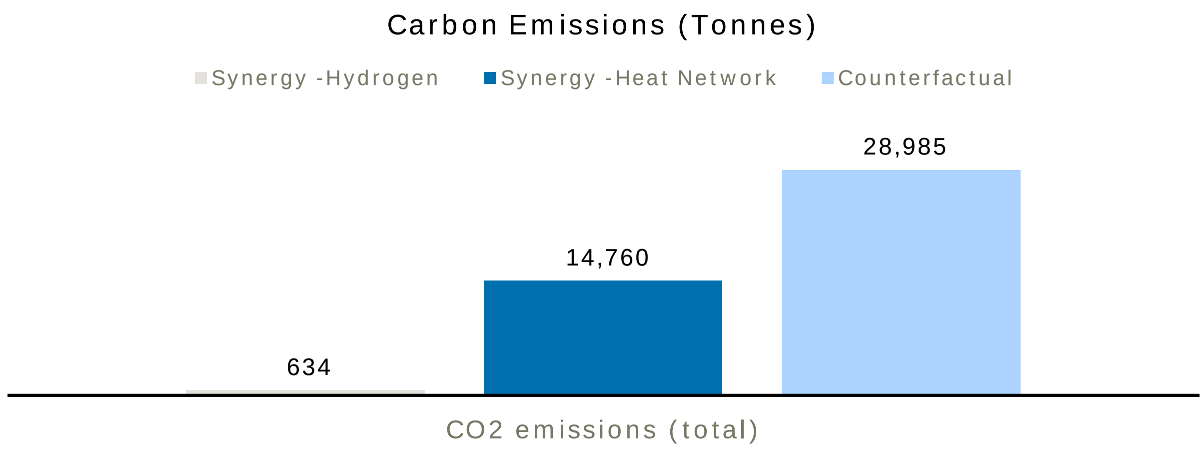
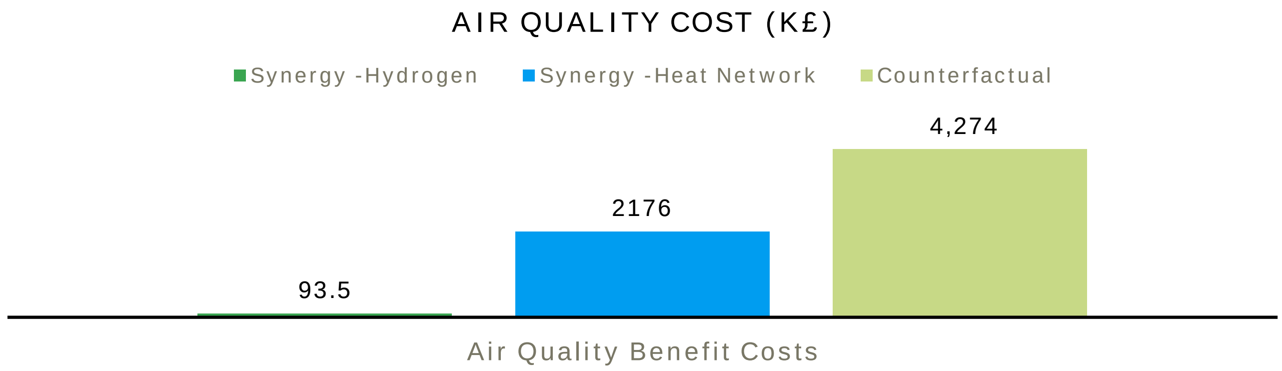
ENVIRONMENTAL RESULTS: SUBSTANTIAL ENVIRONMENTAL BENEFITS



Total Carbon Savings : 13,500 Tonnes



Total Air Quality cost Savings: £2m

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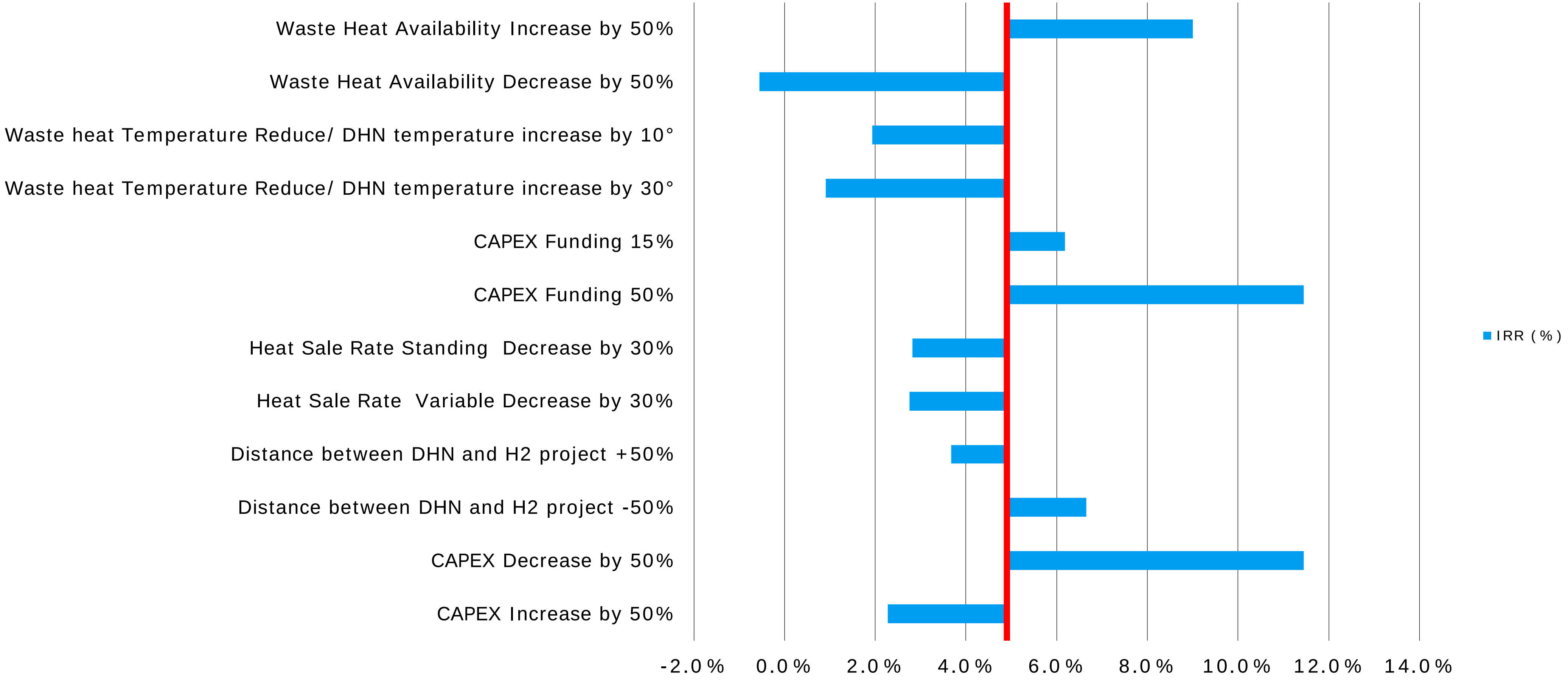
SENSITIVITY ASSESSMENT



NOTE ON

WIDER APPLICABILITY / POTENTIAL SCALE

- To note wider applicability / potential scale, have applied the Synergy Configuration to the projected 2050 Green Hydrogen production estimates.
- 2050 Green Hydrogen production estimated at 249 TWh.
- Assume all Green Hydrogen production assets utilise the waste heat for district heating.

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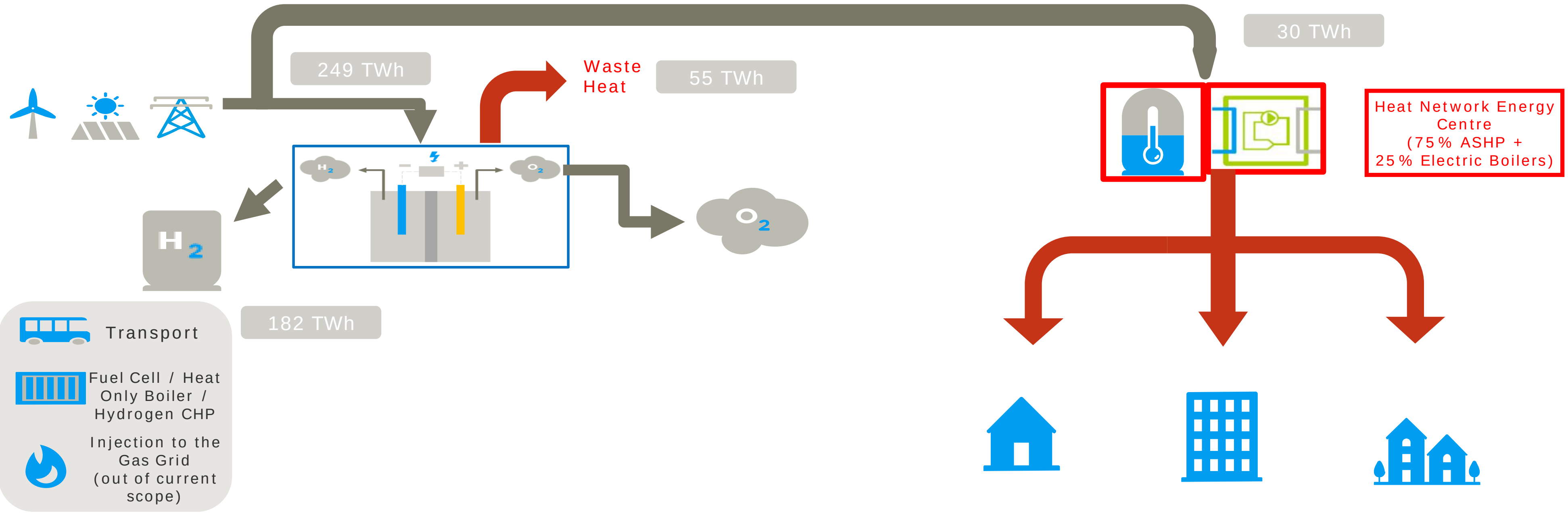
NOTE ON

WIDER APPLICABILITY / TRANSFERABILITY

COUNTER FACTUAL SCENARIO 2050



- Assumes electrolyser waste heat is vented to atmosphere rather than used.
- Assumes a DHN which typically has a greater efficiency than individual domestic ASHP's.

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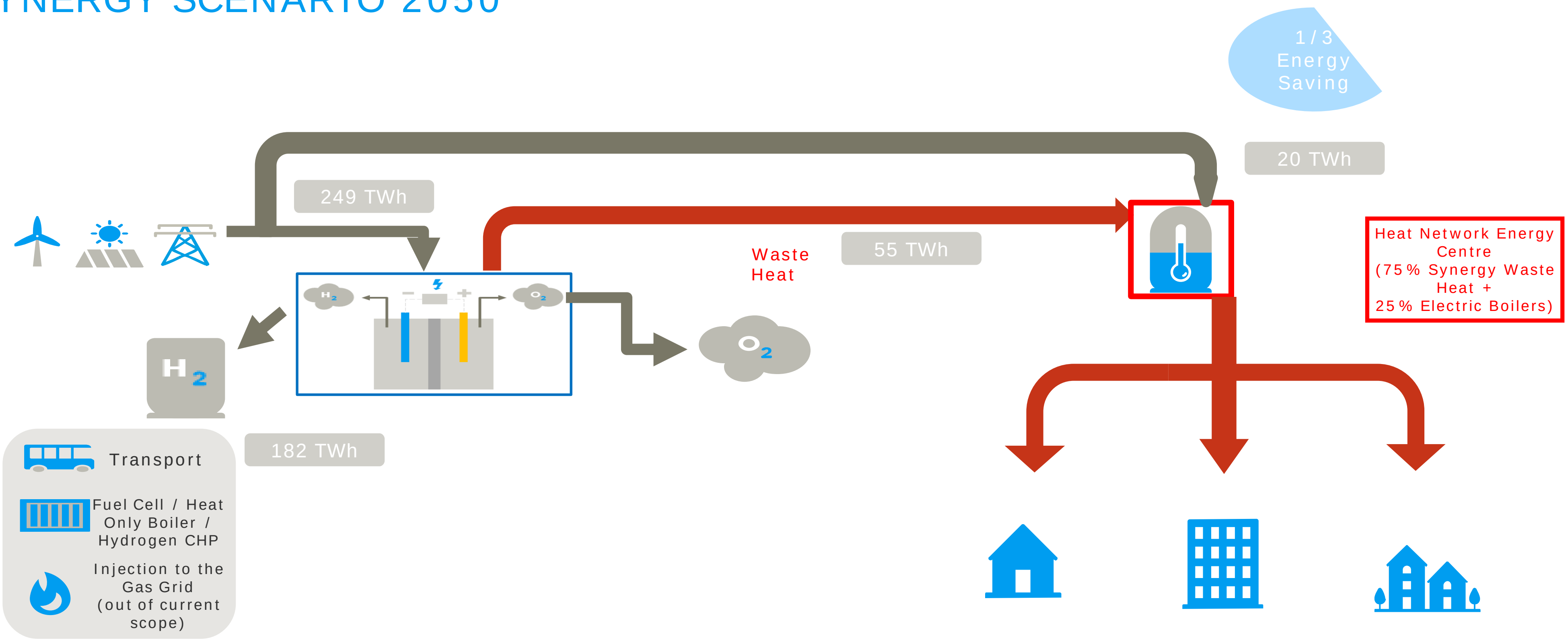
NOTE ON

WIDER APPLICABILITY / TRANSFERABILITY

SYNERGY SCENARIO 2050



SUMMARY OF

WIDER APPLICABILITY / POTENTIAL SCALE

- The Synergy Configuration has considered a standard electrolyser design.
- Therefore, Synergy Configuration could be applied to a large proportion of the projected Green Hydrogen (249 TWh) projects.
- In addition, much of the costs are associated with the DHN, therefore Synergy Configuration would see cost reductions if assets were more strategically located.

- In terms of wider benefits, applying to all Green Hydrogen projects:
  - Electricity Saving: 10 TWh
  - CO_2 savings of 2.2M tonnes per annum, and based on the 2025 carbon grid intensity, 88M tonnes over 40 years.
  - Or the power could of be used to produce 4% more Green Hydrogen.

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Conclusions and Recommendations

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CONCLUSIONS

- South Humber region offers a technically feasible project opportunity to recover waste heat from hydrogen production, and utilise this heat to supply district heating networks.

- For the Hydrogen Generator: Projected an IRR of 14%, with a positive NPV.
- For the Heat Network Operator: Projected an IRR of >4%, with positive NPV.

In addition, in comparison with the counterfactual scenario, identified synergy could:

- Reduce heat costs to consumers by up to 20%.
- Reduce carbon emissions by >50%.
  Therefore, given the forecasted level of hydrogen production in the UK, it can be concluded that synergies of heat recovery from hydrogen production could significantly accelerate decarbonisation of heat in the UK.

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CONCLUSIONS (CONT...)

- The appraisal identified the following Key Sensitivities:
  - Waste heat availability / heat demand;
  - CAPEX; and,
  - Difference in waste heat and heat network temperatures.
- These should be addressed through early planning and stakeholder engagement if the heat recovery from hydrogen production concept is to be investigated further.

- The study also illustrated that heat recovery is possible from both green and blue hydrogen production. However, considering the lower temperature of heat typically available from blue hydrogen production, the returns on investment are likely to be lower.

CONCLUSIONS (CONT...)

- In addition to direct financial and carbon savings, wider benefits include:
  - Public Health Benefits, including reduced electricity-related air emissions for hydrogen and DHN projects. For example, it was estimated that over the 40-year lifecycle, the identified synergy could reduce the social cost of air quality impacts for Stallingborough by up to £2m.
  - Potential to Reduce Fuel Poverty by providing access to low-cost, low-carbon heat to communities adjacent to large-scale hydrogen production projects;
  - Positive contribution towards improving energy security by reducing the electricity demand from the heating sector, and thereby reducing pressure on the National Grid;
  - Positive contribution towards rolling out of offshore wind and large-scale hydrogen production projects by improving their financial performance, with associated positive socio-economic and supply chain benefits;
  - Promoting the case for developing hydrogen production projects near heat clusters, and hence providing an opportunity to developing local clean sources of hydrogen which is seen as a key fuel in decarbonisation of energy and has potential to attract new businesses to the area.
  - Demonstration of the technology within the context of the heat networks and opportunities to roll out across the heat networks in the UK.

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RECOMMENDATIONS

- Given the significant environmental, economic and social benefits, it is recommended to carry out further and more detailed appraisal of the synergy opportunities identified in the South Humber region.

- Local planning authorities should proactively promote and support hydrogen and heat network synergies by developing guidance and requiring its consideration through the planning process for new hydrogen generation projects (e.g. actively encouraging the co-location of new hydrogen infrastructure and heat network energy centres).
- The UK and devolved Governments should include a requirement to consider the feasibility of heat recovery when assessing grant funding applications for hydrogen production projects.
- The UK and devolved Governments should give consideration to making dedicated funding available for the development and delivery of heat recovery from hydrogen production projects.

RECOMMENDATIONS (CONT...)

- Early engagement of stakeholders and planning is the key in making the identified synergies feasible.
- The following steps should be taken during early project development stages for any future studies to develop hydrogen and heat network synergies:
  - Prioritising waste heat recovery from the hydrogen production projects in implementation of the heat hierarchy for the heat networks.
  - Assessing the practical options and business case for waste heat recovery during the early feasibility and FEED (Front End Engineering Design) of hydrogen production projects.
  - Making hydrogen production projects ‘future-proofed’ for waste heat recovery (for example, by specifying electrolysers for cooling water temperatures suitable for heat networks and allowing sufficient space for the future addition of heat recovery equipment).
  - Co-locating hydrogen production projects with heat network energy centres to reduce the initial cost for the heat transmission network.
  - Government and planning authorities requiring offshore wind projects to locate onshore grid connections close to heat networks, energy centres and / or areas of high density heat demand.

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DISCUSSION / QUESTIONS

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