

Aberdeen City Council
Hydrogen for Aberdeen District
Heat Networks Abridged version
Technical Study Report

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Draft

This report takes into account the particular instructions and requirements of our client.

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Contents

| | Page |
|------------------------------------------------------------------|-----------|
| 1 Introduction | 1 |
| 1.1 Network Breakdowns | 3 |
| 2 Benefits and Challenges for the Use of Hydrogen in DHNs | 4 |
| 2.1 SWOT Analysis | 4 |
| 2.2 Hydrogen vs Other Heating Methods | 6 |
| 2.3 Energy Centre Spatial Suitability | 8 |
| 3 Hydrogen System Building Blocks | 9 |
| 3.1 Production Facilities | 9 |
| 3.2 Hydrogen DHN Technologies | 10 |
| 3.3 Hydrogen Transportation and Distribution | 15 |
| 3.4 Hydrogen Storage & Balance of Plant | 16 |
| 3.5 Hydrogen Technology Assessment | 17 |
| 4 Wider System Benefits | 19 |
| 4.1 Skills and Just Transition | 19 |
| 4.2 Demonstration of Hydrogen Heating | 20 |
| 4.3 Maintaining Aberdeen's Position as Energy City | 21 |
| 4.4 Whole System Thinking | 22 |
| 4.5 Anchor Demand to Reduce Hydrogen Costs | 22 |
| 5 Pathways to Net Zero Heating for Aberdeen | 23 |
| 6 Next Steps | 24 |
| 7 References | 26 |

1 Introduction

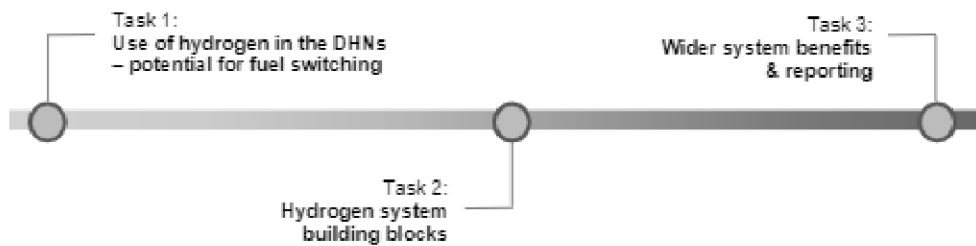
The UK Government's Energy White Paper, the Climate Change Committee's 6th Carbon Budget and Scottish Government Hydrogen Policy statement all identify a key role for hydrogen in achieving net zero. However, there is significant debate on the appropriate applications and scale of deployment of hydrogen and the extent to which it can play a role in decarbonisation of heat. Current UK ambition aims for a 'hydrogen town' by the end of the decade. There is potential, however, to accelerate hydrogen deployment over the next 10 years, particularly as Scotland looks to decarbonise heat in 1 million homes. Hydrogen used for heating has several advantages, including:

- The potential for the use of existing grid infrastructure - the distribution network that has already transitioned to polyethylene pipes can safely transport hydrogen.
- The ability to store hydrogen to meet seasonal fluctuations in heating demand.
- For residential properties with gas boilers, the switch to a hydrogen heating system may be viewed as more straightforward than the switch to a heat pump.
- The overall energy supply system resilience provided by maintaining two energy transmission vectors.
- The wider benefits of a hydrogen economy, where increased hydrogen demand may reduce costs for other end users as well as providing wider economic benefits.

Aberdeen is currently at the centre of the emerging hydrogen economy through ambitious projects such as the Aberdeen Hydrogen Hub and the Hydrogen Bus Project. It is therefore highly likely that Aberdeen will be the focus of investment in further hydrogen projects as a leading hydrogen city.

The feasibility study undertaken will assess the potential hydrogen demand at the current city heat networks and identify technical solutions to successfully integrate hydrogen into the DHNs which are owned and operated by Aberdeen Heat & Power, an independent not-for-profit district heating company. It will also produce an options appraisal for developing hydrogen compared to other emerging carbon neutral technologies. The output will be presented in two phases: an initial technical study of the options for hydrogen conversion (Phase 1) followed by a route map detailing timescales and costs of selected options (Phase 2).

It goes on to identify and test technical options for fuel switching, mapping hydrogen production facilities and reviewing impacts of other key factors. The study covers three key tasks for Phase 1 of the project, as described in further detail below.



Task 1: Use of hydrogen in the DHNs This includes a review of technical and mapping information.

Task 2: Hydrogen system building blocks This will establish the long list of options for building blocks of the hydrogen system. These include production facilities, DHN hydrogen technologies, distribution of hydrogen to the DHN, storage and balance of plant requirements. The identification of options for system components will cover the full hydrogen supply/value chain.

Task 3: Wider system benefits This will consider the wider system benefits for hydrogen, focusing on the Aberdeen area. This will consider the impact of the anchor demand for hydrogen created by the DHNs on the cost of hydrogen production and the additional opportunities that may be created by increasing hydrogen use across Aberdeen.

The report begins with a brief description of the use of hydrogen in the DHN and how this compares to other technology options (Section 2). The main body of the report consists of a description of the building blocks for the Hydrogen for Heat DHN scheme (Section 3), focusing on the hydrogen appliances and options for distribution, storage, and balance of plant. The options appraisal matrices for each of these hydrogen value chain elements are presented. Finally, the report describes the wider system benefits of the Hydrogen for Heat DHN scheme (Section 4) and gives an overview of pathways to net zero heating (Section 5).

1.1 Network Breakdowns

1.1.1 Gas consumption and carbon emissions

The gas consumption for each energy centre and resulting carbon emissions are shown in the figure below.

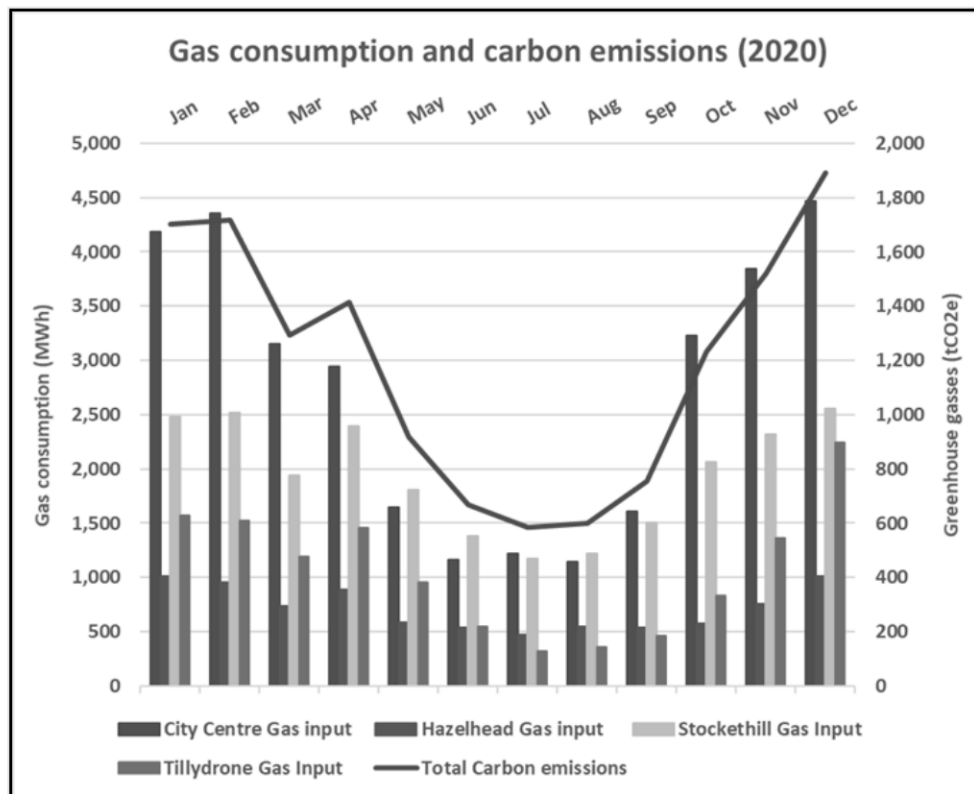


Figure 1: Energy consumption (per energy centre) and total networks(s) carbon emissions

Operation strategy

We understand that operation of the CHP plant is driven by customer heat demand. The resulting co-generated electricity is sold to the electricity network to provide additional monetary income. The CHPs also deliver a carbon benefit by displacing electricity that would otherwise be generated elsewhere by more carbon-intensive generating assets.

As the combined thermal capacities of the boilers are larger than the CHPs, it is likely that in most cases, the CHPs meet most of the baseload demand, where it would also co-generate electricity, and the boilers would provide heat in times of higher demand.

2 Benefits and Challenges for the Use of Hydrogen in DHNs

2.1 SWOT Analysis

A high-level Strength, Weaknesses, Opportunities and Threats (SWOT) analysis of integrating hydrogen into a DHN has been conducted by Arup from both an economic/commercial and technical point of view.

As is shown below, the internal factors (i.e. strengths and weaknesses) were mainly identified technical benefits and drawbacks of implementing hydrogen. In contrast the external factors mainly identified economic opportunities and threats. The main points covered in this analysis were: the wider hydrogen supply chain, the hydrogen units themselves and issues surrounding operation and storage. However, note that this result of this analysis does not account for the scale of plant, which affects the degree of impact of each point identified. This will be covered in Stage 2 in a more energy centre focussed analysis. The results of this analysis are shown below. Note that technical points and economic/commercial points are noted by a “T” and “EC” respectively.

| Internal Environment (i.e. “low-level” points such as asset operation ect...) | | | |
|-------------------------------------------------------------------------------|---------------------------------------------------------------------------------------------------------------------|-------------------|------------------------------------------------------------------------------------------------------------------------------------------------------|
| Strengths (Pros) | | Weaknesses (Cons) | |
| T | Hydrogen technologies have near zero carbon emissions at point of use | T | Some hydrogen technologies (e.g. hydrogen CHPs) may produce some residual emissions (such as Nitrogen Oxides (NO _x). |
| T | Some hydrogen technologies can operate similarly to currently installed assets (e.g. Hydrogen combustion CHP) | T | Potential safety issues associated with high pressure fuel transport and storage (e.g. hydrogen transported via tube trailer may be at 350-700 bar). |
| T | It is often possible to retain electrical generation alongside heat generation | T | Hydrogen is typically expensive to compress due to its low volumetric density (if compressed on-site). |
| T | Provided hydrogen is produced offsite, no significant extra electrical infrastructure upgrades are required (unlike | T | Derating may be required due to knocking – this may result in extra capacity needing to be |

| | | | |
|----|----------------------------------------------------------------------------------------------|----|------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| | those often needed when electrifying heat) | | installed to make up any resulting shortfall. |
| T | Hydrogen has a wide flammability range and can be combusted in a range of fuel-air mixtures. | T | Using hydrogen as a fuel may result in embrittlement of pipework and other auxiliaries, depending on the operating pressures and materials used in the transit system. |
| EC | Using these technologies helps establish a hydrogen economy in the region. | T | The round-trip efficiency to produce electricity from hydrogen (via CHP) is low. |
| | | EC | As with all decarbonisation options, new hydrogen energy conversion assets are predicted to be more expensive than fossil fuel counterparts in the short term. |

Table 1: Strengths and weaknesses of implementing hydrogen in DHN

| External Environment (i.e. “high-level” points such as market forces ect...) | | | |
|------------------------------------------------------------------------------|--------------------------------------------------------------------------------------|---------|-------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| Opportunities | | Threats | |
| T | Can work in tandem with electrification to provide a means of resilience | T | Blue (rather than green) hydrogen may become the preferred hydrogen production method which results in some CO ₂ e emissions. The dominance of blue vs green hydrogen will depend on the requirements for hydrogen production volumes, purity, availability of renewables etc. |
| T | The cost of hydrogen technology is expected to decrease as hydrogen demand increases | EC | Hydrogen is generally less well understood by the public than natural gas |

| | | | |
|----|-----------------------------------------------------------------------------------------------------------|----|----------------------------------------------------------------------------------------------------------------------------------------------------------|
| EC | The cost of hydrogen will benefit from a decreasing cost of renewable electricity. | EC | The lower round-trip efficiency of hydrogen production may discourage general uptake in favour of electrification |
| EC | There are numerous ways to produce hydrogen and local/existing infrastructure could be taken advantage of | EC | To maintain long-term commercial viability, the cost of hydrogen generation and energy conversion technologies and storage will have to decrease quickly |
| EC | Can complement other renewables as they are installed in the future (e.g. solar) | EC | The superior method of fuel supply for hydrogen is still generally undecided (e.g. road tankers, via the gas network or by separate pipeline) |
| | | EC | Legislation may not keep up with technological advancements in hydrogen energy production and supply |

Table 2: Opportunities and threats of implementing hydrogen in DHNs

2.2 Hydrogen vs Other Heating Methods

2.2.1 Hydrogen

With hydrogen-fuelled methods (with no on-site generation), depending on the technology, there can be little to no impact on the DHN side. This is particularly true in the case of 20% vol. hydrogen supplied by the local gas provider, although flow control equipment, such as valves, may need to be replaced. 100% hydrogen fuelled options would require various levels of retrofits and upgrades regardless of the prime mover(s) used for heat generation. In this case it is likely that the original natural gas delivery pipes would have to be upgraded or replaced to meet the same energy output due to the lower volumetric density of hydrogen. Alternatively, if the system design pressures are sufficient, an increase in flow velocity could be utilised to increase fuel throughput.

A move to hydrogen would also mean that hydrogen storage would likely need to be accommodated and new auxiliary equipment, such as leak detection systems, installed.

In most applications, carbon emissions will be minimal when using hydrogen for heat generation. However, depending on the heat conversion unit, NO_x

emissions may still be present when hydrogen is combusted (unless in pure oxygen).

2.2.2 Electrical-based heating

Electrical heating systems, such as those provided by electrode boilers and heat pumps, are generally considered simpler, cheaper, and more efficient solutions than hydrogen options to implement, as only an electrical connection is required. However, depending on the amount of power required, additional or upgraded substations may be necessary incurring substantial costs. The electrical capacity delivered by the local Distribution Network Operator (DNO) is limited by the current or planned capacity of the local distribution infrastructure. Additionally, an alternative back-up fuel with appropriate generation units would be required for resilience.

The amount of electricity required, and resulting carbon produced, for heat generation depends on the type of heat conversion unit used. For example, an electrode boiler will typically require more electric energy and capacity than a heat pump, although the exact level depends on the external environmental conditions. Importantly, there are no emissions at the point of use when using electric heating, although in the case of heat pumps there is the risk of refrigerant leak which has a high global warming potential – obviously varying with the type of refrigerant used. Additionally, regarding heat pumps, they traditionally struggle to meet the high temperature requirements of district heating networks. This may result in consumer-side retrofits if they were to be used to supply heat to the network.

Electricity is also relatively difficult to store compared to hydrogen (and other fossil fuels) due to storage degradation and therefore presents a vulnerability to the DHN operation if electricity supply is interrupted for a long period of time.

2.2.3 Biogas

Biogas-based heating typically requires a geographically close source of feedstock for fuel production. This is typically done via anaerobic digestion using sewage or bio-crops as a feedstock. For this reason, it is typically less well suited for metropolitan areas. Using the produced biogas is relatively simple and has the same considerations as that of a hydrogen solution although production requires strict temperature controls. Depending on feedstock, impurities may also be present which require risk management.

Whilst biogases can be considered carbon neutral, at the point of use biogas produces greenhouse gases when combusted so air quality restrictions need to be met, particularly in densely populated areas.

2.2.4 Aberdeen city considerations

Situated in the north of the UK, air and water temperatures are typically lower in Aberdeen than other British cities. As such, solutions that are temperature dependent may not be able to operate at their optimum output. Lower air and water temperatures negatively affect the Coefficient of Performance (COP) of Air-Source Heat Pumps (ASHPs) and Water-Source Heat Pumps (WSHPs). Biogas production units that require a temperature of 37°C would also be negatively affected by lower ambient temperatures.

Planned building efficiency measures may also impact the choice of heat generation unit technology. Efficiency measures (such as low temperature radiators) on the consumer side may make lowering the flow and return temperatures viable for the DHN operator. This would also impact heat pump solutions that historically have struggled to meet the required flow temperatures for a more commercially viable option.

2.3 Energy Centre Spatial Suitability

Retrofitting or replacing assets with hydrogen-fuelled technologies also raise issues surrounding the spatial requirements within the energy centre as well as required auxiliary technology needed. These include:

- A hydrogen storage facility would be required for incoming hydrogen deliveries if supplied by tankers. Even if not delivered via tanker, there may still be a storage requirement for resilience. This storage area would have to be equipped with leak detection systems and suitable ventilation.
- *Appareils destinés à être utilisés en ATmosphères Explosives (ATEX)* ratings will have to be adhered to for any hydrogen storage. For hydrogen storage hazardous zones can be substantially larger than those for natural gas storage.
- Conversion to hydrogen-fuelled assets may result in derating to avoid issues such as knocking, which will decrease the asset lifespan. As such, an extra top-up unit (boiler or CHP) may be required to make up the resulting shortfall. Therefore, the energy centre will require space for installation and operational maintenance of this additional equipment.

3 Hydrogen System Building Blocks

3.1 Production Facilities

3.1.1 Aberdeen city hydrogen refuelling stations

The hydrogen refuelling and production stations listed below are currently used to meet the short-term demand for bus and public vehicle fleets (currently 500 kg/day H₂ demand) while the Aberdeen Hydrogen Hub is in development. Due to the small capacity and focus on transport-only applications, these have not been considered as a feasible source of hydrogen production for the DHN.

- **Aberdeen City Hydrogen Storage (ACHES)** - Hydrogen produced via a HySTAT-60 315 kW electrolyser. The station can produce a maximum of 130 kg/day at 350 and 700bar, capable of refuelling five 26 kg capacity buses per day. It has 100 kg of storage at 500 bar and 50 kg of storage at 900 bar.
- **Kittybrewster** – Hydrogen is produced by three Hydrogenics Hystat60 electrolysers [1]. The station can produce 360 kg/day, capable of refuelling thirteen 26 kg capacity buses per day, and has been upgraded to allow 700 bar re-fuelling for cars as well as 350 bar pressure for vans, trucks and buses [2][3].
- **TECA Energy Centre** - Hydrogen is produced via a HySTAT H/10 electrolyser. The station can produce 200 kg/day at 200 bar as standard. It has a 330 kg storage facility onsite. A 1.4 MW fuel cell is installed at TECA, providing combined cooling, heating and power. The unit reforms biomethane to produce hydrogen, which is used in the fuel cell [4]. Using this hydrogen as part of short-term arrangements for refuelling additional buses, tube trailers, vans and small vehicles is currently under consideration.

3.1.2 Aberdeen hydrogen hub (AHH)

ACC are planning the delivery of a commercial-scale green hydrogen production, storage and distribution facility. This will use electrolysis, directly powered by local renewable energy. Site identification and selection is currently underway, with five sites around Aberdeen being considered (Appendix A).

Electrolyser capacity of 8-10 MW is planned by 2032 (approximately 3,750 kg/day). The AHH will initially be used to meet road transport demand (Phase 1) and will expand into heating applications (Phase 2) and eventually rail and maritime applications alongside industrial and export opportunities (Phase 3). The total projected hydrogen demand used as a basis for the first business case is 3,500 kg/day by 2030 (145 buses, 800 cars and 70 HGV's in and around the Aberdeen area) [5]. However this demand will increase significantly with the addition of heating. For example, the DHN annual gas usage is 155,557

MWh/year which equates to additional 12,798 kg/day of hydrogen production, more than three times the projected demand for the AHH.

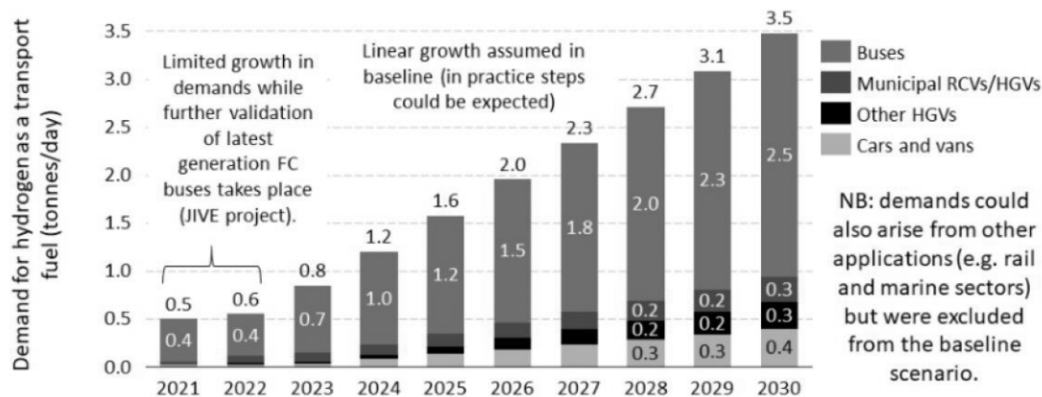


Figure 2: Fuel demands to be met by the Aberdeen Hydrogen Hub (graph provided by Aberdeen City Council [5])

As a large, centralised production facility, AHH aims to enable economies of scale to allow hydrogen to be produced at around cost parity with current conventional transport fuel prices (£6/kg of hydrogen). In addition to this, there is the potential to benefit from policy mechanisms such as Renewable Transport Fuel Certificates as a further source of income. To deliver conventional fuel parity, the cost of renewable electricity used for hydrogen production is being targeted at £45/MWh [5].

3.1.3 Oxygen usage

An additional product of electrolysis of water for the production of hydrogen is oxygen. This could be cleaned, pressurised, and bottled. End uses could include medical-grade oxygen supplied to hospitals in Aberdeen, oxygen supply for underwater operations or utilising oxygen in wastewater treatment facilities. However, it is worth noting that production of medical-grade oxygen is very tightly regulated, therefore only economical on a large scale or in collaboration with a supplier who is already licenced.

3.2 Hydrogen DHN Technologies

3.2.1 Up to 20 % vol. hydrogen blend

Trials are currently underway around the UK that are exploring the possibility of blending 20 % vol. hydrogen into the natural gas pipelines. Following on from a similar trial at Keele University, UK, a trial is currently underway where more than 670 homes and some commercial and public buildings in Winlaton are taking part in replacing their current natural gas supply with a 20% vol. hydrogen blend. This will be the first public natural gas network to introduce a hydrogen blend [10]. If this deployment can be replicated on a large enough scale to satisfy the DHN energy demand and still be compatible with the existing/planned

assets, this option potentially presents a relatively cheap and non-invasive way to reduce carbon emissions (by approximately 7% if 20% vol. hydrogen was blended into the natural gas supply) [11]. There may be some focussed upgrading required depending on the age and materials used in an asset, however.

Alternatively, hydrogen injection into the natural gas supply could occur within the energy centre if the trial doesn't result in a large-scale rollout. To do this, enabling technologies would have to also be present such as: electrolyzers, hydrogen storage (likely as a compressed gas) and a pressurised hydrogen gas injection point. This would naturally be a much more complex and expensive pathway for the DHN operator than utilising pre-hydrogen blended fuel supplied by a third party.

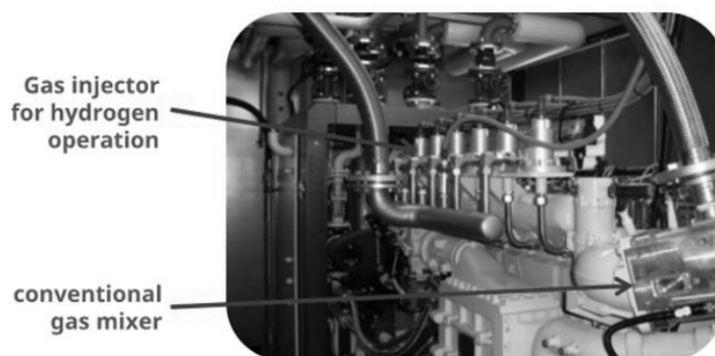


Figure 3: Gas injector into a reciprocating hydrogen combustion CHP (2-g) [12]

3.2.2 New hydrogen boilers

Hydrogen boilers are a simple technology currently being considered as a potential future alternative to the use of natural gas boilers for domestic and industrial heat generation.

The operating principle is the same as a conventional gas boiler where a fuel-air mixture (in this case hydrogen) is combusted to generate heat that in-turn raises the temperature of feedwater. Due to the hydrogen content in the fuel mixture, some water is also generated. Note that unless hydrogen is burnt within pure oxygen, some NO_x will also be emitted, and these should be assessed against any air quality legislation in the region.

It should be noted that many “new” boilers are marketed as “hydrogen-ready boilers” which will be able to accept 100% hydrogen once the supply chain has been established. These are commercially available from certain manufacturers [13]. It is assumed that these boilers would be designed to avoid many fuel switching issues such as embrittlement and efficiency/heat output drops that would result from a gas boiler to hydrogen boiler retrofit. Although some retrofits may still be necessary, such as burner replacements, piping and/or valves depending on the manufacturer.

3.2.3 Hydrogen CHP

Reciprocating CHP

A reciprocating hydrogen combustion CHP unit relies on the same process as current natural-gas fired CHPs. Hydrogen is injected into the cylinder of an Internal Combustion Engine (ICE) and combusted to drive the engine and connected generator with exhaust heat used to raise the temperature of feedwater.

Due to the hydrogen content in the fuel mixture, some water is also generated. Note that unless hydrogen is burnt within pure oxygen, some NO_x will also be emitted, and these should be assessed against any air quality legislation in the region.

Turbine CHP

A hydrogen turbine CHP relies on the same process as current natural-gas turbines. They are typically used to raise steam by use of a waste heat recovery boiler from the hot exhaust gas produced by the turbine but they can also be used to produce hot water directly.

An electrical generator is coupled with the gas turbine to generate electricity from the rotation of the power shaft during operation.

Due to the hydrogen content in the fuel mixture, some water is also generated. Note that unless hydrogen is burnt within pure oxygen, some NO_x will also be emitted, and these should be assessed against any air quality legislation in the region. Many of the same issues that reciprocating hydrogen combustion engines face are also present in the turbine configuration such as a higher magnitude heat transfer, decreasing asset life, and autoignition risk, in the case of retrofitting [14].

3.2.4 Fuel cell CHP

There are many different types of fuel cells with differing applications and advantages and disadvantages. The three fuel cells that are likely suitable for distributed zero carbon heat and electricity generation are: Solid Oxide Fuel Cells (SOFCs), Molten Carbonate Fuel Cells (MCFCs) and Phosphoric Acid Fuel Cells (PAFCs) due to their high operating temperatures that may be suitable for heat recovery. However, the operating principle between all of them is relatively similar in that they consist of an anode, cathode, and electrolyte.

The operation of fuel cells centres around a chemical reaction where two elements bond to create another compound. In the case of using hydrogen as a fuel, this usually involves stripping the electrons from a hydrogen molecule via oxidation and introducing them to an oxygen molecule to react and produce water, electricity, and heat. This does vary slightly depending on the fuel cell type, for example in the case of solid oxide fuel cells, the oxygen also is reduced to oxygen ions. Depending on the type of fuel cell, temperatures ranging from

150 – 1,000°C can be reached. A brief comparison between the previously mentioned fuel cells types is shown below:

| Operating temperatures (°C) | Electrical efficiency (LHV) | Advantages | Disadvantages |
|-----------------------------|-----------------------------|----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| <i>PAFC</i> | | | |
| 150-200 | 40 % | <ul style="list-style-type: none"> - More tolerant of fuel impurities from reformed hydrogen. | <ul style="list-style-type: none"> - Expensive catalysts that need to be corrosion resistant - Lower power to weight ratio compared to other fuel cells - Long start up time |
| <i>MCFC</i> | | | |
| 600-700 | 50% | <ul style="list-style-type: none"> - Relatively low capital cost as platinum catalyst isn't required | <ul style="list-style-type: none"> - Supply of CO₂ required - Electrolyte is a very hot liquid and needs safety considerations. - Long start up time - Stack degrades quickly due to aggressive chemistry |
| <i>SOFC</i> | | | |
| 500-1,000 | 60% | <ul style="list-style-type: none"> - Has a solid electrolyte so pumping isn't required - Relatively low capital cost as platinum catalyst isn't required | <ul style="list-style-type: none"> - Very long start up time (≥ 12 hours) - Requires heat shielding - Ceramic parts can't withstand heating and cooling cycles very well |

Table 3: Fuel cell comparison [15][16]

Often these fuel cells are containerised into single modular units as shown below.



Figure 4: Doosan Purecell Model 400 [17]

Retrofitting Reciprocating CHP

According to stakeholder engagement, the key component to retrofit is the fuel injection valve into the cylinder of the engine to ensure injection pressures are suitable for hydrogen rather than methane.

Hydrogen can either be injected during the intake stroke or during the compression stroke of the internal combustion engine which both have advantages and disadvantages associated with them. Both cases introduce issues regarding engine knock and possible pre-ignition [18].

Depending on the unit model and materials used by the CHP manufacturer, additional retrofitting activities may be required such as:

- Auxiliary pipe(s) replacement to reduce permutation and corrosion. This is particularly relevant if impurities are present in the fuel.
- Intake air system to be modified as less air is needed to combust hydrogen.
- Possibly turbocharger modification depending on the concentration of hydrogen in the fuel.

Retrofitting Boilers

Previous studies have been conducted that explored the retrofitting of commercial scale boilers to using various blends of hydrogen, including 100% vol. The following points were found when fuel switching [19]:

- There is a lower air requirement compared to natural gas for combustion so the turndown capability of fans should be considered
- Some potential limitations on the turn down capabilities due to a higher hydrogen flame velocity
- Impact on the requirements for shut down valves considering the higher potential for leakage

The main retrofitting activities that are reportedly needed to be carried out for a 100% vol. hydrogen conversion are [19]:

- New burners and relevant modifications to the floor
- Combustion air ducts and piping
- New fuel skid
- Flame scanner replacement
- Modification of fuel feed piping

Thermal Storage

It is unlikely that thermal storage would need any significant retrofitting activities applied, provided that the required heat and temperatures can be produced with hydrogen-fuelled units in a like-for-like fashion. However, during other retrofitting activities, the thermal storage would have to be decoupled from the heat generation plant.

3.3 Hydrogen Transportation and Distribution

3.3.1 Existing gas network

Hydrogen can be injected into the existing gas grid, either as a blend or through conversion to 100% vol. hydrogen. This tends to suit larger volume, long-distance transport requirements. However, if using hydrogen in a fuel cell, pipes can be a less attractive method of transport due to the potential for the hydrogen to pick up impurities that would damage the fuel cell.

Reusing existing gas network infrastructure can be a cheaper and less disruptive option, as long as there are no sensitive end users who cannot use hydrogen (e.g. where commercial natural gas is used as a process feedstock rather than a fuel, or where fuel switching may be problematic for commercial or industrial appliances). It has been indicated in early trials that a blend of up to 20% hydrogen can be injected in the gas network without requiring major modifications to end user appliances, including boilers and gas cookers [20]. However, using steel transmission pipes for higher blends of hydrogen can cause issues with embrittlement and cracking, depending on the operating temperature and steel grade. An asset assessment would therefore need to be undertaken to determine compatibility with hydrogen, and the pipes may need to be replaced with polyethylene pipes, along with any valves and fittings which may be susceptible to leakage from the smaller molecule size compared to natural gas. Hydrogen also cannot be used in original cast iron gas distribution pipelines mainly due to leakage at the joints. However conversion of these distribution networks to polyethylene is already underway.

3.3.2 New pipeline

A further option for hydrogen delivery is to install a new purpose-built polyethylene pipeline to transport hydrogen from the production site to the DHNs. This has the advantage of keeping hydrogen separate from the natural gas network, allowing use of 100% hydrogen more quickly. However, a new pipeline network would likely be more expensive than reusing the current gas network, depending on the location of the production facility in relation to the energy centres.

3.3.3 Road transport

Compressed hydrogen gas at 350 bar or 700 bar can be transported in high-pressure tube tankers [21]. This method of delivery tends to suit smaller volumes of hydrogen being transported over shorter distances to discrete demand centres.

Access space for heavy goods vehicles is required at the delivery point. Additionally, hydrogen can be transported as a liquid in tankers, which increases the energy density once it has been cooled below -253°C . However, this requires additional energy for the liquefaction process and has issues with boil-off losses.

3.4 Hydrogen Storage & Balance of Plant

3.4.1 Tank storage

When hydrogen is used for heating applications, storage will be required to meet peaks in demand. Hydrogen can be stored in stainless steel or composite tanks as a compressed gas at relatively low pressure (0-150 bar) or at higher pressure (150 – 1,000 bar). This form of storage is suitable for stationary applications where there is sufficient space available as the containers will need to be located outside at a safe distance from structures, ventilation intakes and vehicle routes. However, compressing hydrogen gas requires some additional energy input, reducing the overall system efficiency.

Hydrogen can also be cooled below its boiling point of -253°C and stored in liquid form. This increases the energy density of the hydrogen from 1.4 kWh/litre at 700 bar to 2.3 kWh/litre as a liquid [21], thereby enabling a better energy content to volume ratio. However, cryogenic cooling is expensive and energy intensive, using approximately 1/3 of the embedded energy to cool the hydrogen, based on current technology. A gasification facility to convert the liquid hydrogen back to gaseous form for use in the CHP units would also be required. In addition, a small amount of liquid hydrogen can be lost due to boil off.

3.4.2 Other storage options

Underground storage

Hydrogen can be stored underground, for example in salt caverns, depleted oil wells, repurposed natural gas fields or aquifers. This is most effective for large scale storage but is only possible in locations with appropriate geological features. The University of Edinburgh is currently investigating storage in porous rock through the HyStorPor project [22].

Line pack

Line packing, increasing the pressure in the pipeline network, is a well-established storage method already used for storing natural gas within the gas transmission lines and is suitable for small scale storage. However, bulk storage is preferential for hydrogen due to the poor compressibility of hydrogen requiring a significant length of pipe for effective storage.

Liquid organic hydrogen carriers

Liquid organic hydrogen carriers (LOHC) are organic compounds that can absorb hydrogen onto their surface through a catalysed hydrogenation reaction and store it in liquid form at ambient temperature and pressure. The reaction takes place at

elevated temperature and pressure. Examples of compounds used include methanol, toluene and methylcyclohexane, among others. However, this technology is currently at an early stage of development and so would not be immediately available for use in the DHN.

3.4.3 Balance of plant requirements

Odourisation requirements

Similar to natural gas, hydrogen cannot be detected by smell and is not visible to the human eye. For safety purposes odourant will need to be added to the hydrogen prior to distribution. The odourisation systems for hydrogen are similar both in operation and in size to those used for natural gas.

Compression

In order for hydrogen to be stored as a compressed gas, a compressor is required to boost the pressure of the hydrogen. Depending on the type of storage employed, this could either be to relatively low pressure (30 bar) or high pressure (200-900 bar). Although several technologies exist to compress hydrogen, it is more energy intense than compressing most other gases. Therefore, compressing hydrogen to higher pressures can be a significant parasitic load in any system reducing overall efficiency. In addition, for very high-pressure applications, an extensive cooling system may also be required to remove heat produced in the compression process.

Pressure reduction

Prior to use in most stationary hydrogen applications, the stored, pressurised hydrogen needs to have the pressure reduced to the levels required by the consuming appliance. Similar to odourisation systems, these systems are analogous to those employed in the natural gas sector, however this does not require pre-heating for hydrogen.

3.5 Hydrogen Technology Assessment

This section details the results of the hydrogen building block technology assessments. Each technology was assessed based on the methodology outlined below, the results of the assessment have been presented in the subsequent sections, each one addressing a different system building block.

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4 Wider System Benefits

Hydrogen is set to play a key role in decarbonising the global energy system. Hydrogen will complement increasing electrification of the energy system by helping to decarbonise sectors that are hard to electrify and by creating a more flexible, resilient, and integrated energy system.

The UK Government's Energy White Paper and the Ten Point Plan, the Climate Change Committee's (CCC) 6th Carbon Budget, The Scottish Government's Climate Change Plan and Hydrogen Policy Statement all assert the essential role hydrogen will play in achieving net zero.

The rollout of hydrogen in all these sectors is a developing and while there are a number of high potential applications in the short term, there is a degree of uncertainty regarding the areas in which hydrogen should play a role in the longer term. Determining the appropriate applications for hydrogen in a net zero energy system requires an understanding of whole system economics, technology development and user requirements.

Building evidence through demonstration and delivery of early projects is critical to informing the planning and delivery of decarbonisation to meet challenging 2030 and 2045 decarbonisation targets.

There are a range of potential benefits linked to the integration of hydrogen into Aberdeen's DHN. These could have a positive impact not only on the energy transition in Aberdeen and the North East (NE), but also in securing Scotland's place in the hydrogen economy.

4.1 Skills and Just Transition

A Just Transition considers the creation of jobs and social/economic benefits associated with the energy transition alongside delivery of the lowest cost decarbonisation solution. Net-zero will result in a major shift away from a carbon-based economy to a green economy, requiring different skills and economic activities.

- A hydrogen based DHN creates the opportunity for new jobs/skills creation in areas such as manufacturing, construction and maintenance. In addition, it will support diversification and growth of businesses already established.
- As Aberdeen and the NE is already a major energy industry hub, particularly the offshore and Oil and Gas (O&G) industries, talent can be developed and retained in hydrogen-based services and technologies (aligning with skills already present in offshore/O&G industries).
- In particular, the production of blue hydrogen with Carbon Capture Utilisation and Storage (CCUS) will provide the opportunity for transition and diversification in the oil & gas sector in Aberdeen, supporting

industrial decarbonisation in a way which encourages continued prosperity.

- Many of the supply chain elements required for blue and green hydrogen production and CCUS already exist in Scotland's O&G industry, and it is important to ensure that industry supply chains within NE and wider Scotland are maintained and expanded to maximise the social and economic benefits from the transition.
- Integration of hydrogen into the DHNs presents the opportunity to involve energy consumers, stakeholders and local communities in the energy transition, with opportunities for education and engagement.
- There is the potential to reduce heating costs for consumers which will create positive social and health benefits and reduce energy poverty.
- A green economic recovery is a focal point for both politicians and business as we emerge into a post-COVID world, and hydrogen can significantly contribute to this goal for Aberdeen.

4.2 Demonstration of Hydrogen Heating

There are several advantages to using hydrogen for heating. The flexibility and storage potential offered by hydrogen could be key to addressing inter-seasonal and diurnal heating demand. In addition, the existing gas distribution network can be repurposed to hydrogen, potentially easing the transition from natural gas. However, an evidence base must first be developed to support longer term policy and investment decisions, and the integration of hydrogen in Aberdeen's DHN could play a key role in this.

- The DHN would demonstrate the practicalities of implementing a city-wide hydrogen heating system, such as
 - Using the existing gas infrastructure that has already transitioned to polyethylene pipes to safely transport hydrogen (gas networks currently connect around 80% of households in Scotland [23]).
 - The ability to store hydrogen to meet seasonal and daily fluctuations in heating demand.
 - The switch from gas boiler to hydrogen boiler in residential properties (viewed as potentially less impactful on consumers than installing a heat pump).
- The project could also demonstrate the overall system resilience provided by maintaining two energy-transmission vectors (gas and electricity).
- Implementing hydrogen in the DHN will be a signal of ambition to provide industry and investor confidence in the future of hydrogen in the gas networks. If the indicators are positive, the use of hydrogen in domestic,

commercial and industrial space heating could play an important role in unlocking blue and green hydrogen production.

- Dense population and extensive infrastructure provide opportunities for scale economies from aggregating demand.

4.3 Maintaining Aberdeen's Position as Energy City

Aberdeen is already leading the emerging hydrogen economy within the UK, through flagship projects such as the AHH and the Hydrogen Bus Project. The Ten Point Plan has identified an ambition to create the first town run entirely on hydrogen by the end and for 5GW of low hydrogen production by the end of the decade.

Aberdeen could build on this success and positioning to become the UK's hydrogen town, become a centre for production of hydrogen, with potential to export blue hydrogen nationally and green hydrogen globally, and associated skills, products and services. If deployment is slow, there is a risk that skills and manufacturing will be developed quicker elsewhere. Therefore, a hydrogen DHN could enable Aberdeen to capture the economic value from hydrogen activities.

- The Aberdeen Energy Transition Vision states that Aberdeen is aiming towards 'Net Zero City' status by 2045 and thereafter moving beyond net zero to deliver 'Climate Positive City' status. It will also be Climate Positive Advocate 'playing its full part in limiting average global warming to 1.5°C' [24]. Hydrogen DHNs take an important step achieving this aim by decarbonising a significant part of the challenging heat sector in Aberdeen.
- Implementing a hydrogen heating system creates an advantage for Aberdeen/Scotland in the hydrogen sector as skills, products and services will be developed early.
- Hydrogen heating will create demand which will further cement Acorn's status as the primary producer of blue hydrogen in Scotland, which can provide a low-cost supply at volume in the short-term.
- The North East has an abundant supply of renewables particularly onshore and offshore wind from existing and new licenced developments identified through ScotWind. Creation of demand at scale can also create a route to market for green hydrogen production that will enable cost reduction realisation and support economic growth.
- Creation of supply chains close to deployment has the potential to attract manufacturing activity to Scotland for electrolysis systems or key demand applications like buses.
- Early development and cost reduction of the hydrogen could lead to the opportunity to export hydrogen to Europe, creating significant value. The Scottish Hydrogen Assessment estimates that a 'Green Export' scenario

could deliver £25bn in total Gross Value Added (GVA) and 312,000 jobs to the Scottish economy by 2045 [25].

4.4 Whole System Thinking

For the energy transition to be a Just Transition it is critical to consider the best decarbonisation solution for each application. There are a number of alternative options which could be utilised to decarbonise the district heating network and heating more generally in Aberdeen. To really understand the optimal economic and deliverable application it is critical to consider the whole system impacts.

The implementation of hydrogen-based heating will complement the wider energy system in Scotland, including increasing electrification of the transport and heat sectors, by improving system flexibility and resilience.

- The production of hydrogen utilises Scotland's vast resource of renewable energy, particularly offshore and onshore wind in the NE.
- Hydrogen provides more overall system flexibility, storage capacity and better utilisation of existing infrastructure.
- Hydrogen will complement increasing electrification by improving system flexibility and resilience, allowing better management of supply and demand.
- Scotland could be an exporter of hydrogen to countries in Europe with low energy resources. When considered in the context of its proximity to potential European export markets, such as Germany, and the existing O&G import and export infrastructure, this provides a significant export opportunity.

4.5 Anchor Demand to Reduce Hydrogen Costs

Injection of hydrogen or full conversion of the gas networks to provide heating would present a significant scale of demand to justify investment in production at scale. The DHNs could provide an anchor load in Aberdeen, in addition to the growing transport demand, to stimulate investment in hydrogen production.

However, diversified demand, including transport and wider domestic/commercial and industrial heating, may be required to enable a resilient business model. As mentioned above, deploying hydrogen-based heating also has the potential to stimulate assembly or manufacturing, allowing early development of skills and supply chains to enable and support the hydrogen transition.

5 Pathways to Net Zero Heating for Aberdeen

The Scottish Government has targeted 75% carbon emissions reduction targets by 2030 and net zero emissions by 2045. Therefore, there will be a need to decarbonise heating systems in Aberdeen beyond the DHNs. This will be linked into the decarbonisation of the gas network across Scotland, or a move to other forms of heating. Achieving net zero across the energy system will require a combination of decarbonised gas and electrification options.

In the Update to the Climate Change Plan (2018-2032) the Scottish Government outlined the emissions reduction required in each sector of the economy to meet the 2030 emissions reduction target [25]. The draft Heat in Buildings Strategy adds further detail on what the 2030 emissions reduction target means for heat in buildings, stating that at least 1 million homes currently using mains gas and 50,000 commercial properties will need to convert to low carbon forms of heating by 2030 [27]. These low-carbon forms of heating could be electrified heating, heat networks or hydrogen.

The current hydrogen deployment pathway based on existing policies and strategies of the UK and Scottish Governments sees the delivery of a 100% hydrogen 'town' and hydrogen being used in industry by 2030. In this scenario much of the decarbonised heating required in Scotland by 2030 would be delivered through electrification or heat networks, limiting the role of hydrogen in the short term, and ultimately reducing the role it could play in the long term, as homes would be taken off the gas network to move to electrified heating solutions or heat networks.

An alternative hydrogen deployment scenario could see large areas of Scotland converted to 100% hydrogen by 2030, using hydrogen transported through the gas network to meet a large proportion of the zero-carbon heating requirement as well as industrial and transport demands. The remainder of the natural gas network could also be converted after 2030, to support the 2045 net zero target.

The actual scenario is likely to be a combination of the two. Whole system planning is key to determining which decarbonisation options are most appropriate and should consider all technology options, including electrification and decarbonised gas. Industry and government are currently working on planning and gathering evidence to support decision making around the most appropriate pathway. Currently this is relatively uncertain, although heat pumps are often referred to as the default option as this is a technology that is available today. Decisions around the use of hydrogen for heating are not expected until the mid-2020s as outlined in the UK Government's Energy White Paper [28].

To support a hydrogen pathway several projects are currently investigating the feasibility of using hydrogen to decarbonise heat, transport and industry, and will be able to provide technical and economic evidence by 2024/25. There is also further evidence required on hydrogen storage and commercial and industrial appliances. Planning will evolve over the next decade informed by evidence collected from demonstration and trial projects across all technologies, the AHH

and district heat network pilot project will form part of the evidence base. The Scottish Government will also consider the wider social/economic benefits of any net zero pathway to ensure a just transition.

If hydrogen is to form a large part of delivering the 2030 emissions reduction target, then it is likely that there will be sufficient hydrogen available in the gas network to supply Aberdeen's district heating networks. It is expected that if hydrogen is to play a large role in 2030, Aberdeen would be one of the first cities to convert given the proximity of hydrogen supplies, with a conversion option described in SGN's Aberdeen Vision Report [7]. If the decision is made to utilise hydrogen for heat, then all the appropriate support mechanisms should be put in place to make this palatable for consumers and businesses, this should include appropriate support for district heat networks fed by hydrogen. Alternatively, if hydrogen does not form a significant part of the 2030 emissions reduction target, then it is more uncertain as to how the district heat networks would be supplied by hydrogen in the long term. The long-term supply of hydrogen will be explored further in Phase 2 as we consider how the district heat networks may convert and receive a hydrogen supply.

6 Next Steps

The information summarised in this report will be taken into Phase 2 which will focus on determining the best hydrogen options for the DHN energy centres, as well as identifying a preferred pilot project. To assess the best option for each energy centre we will take into account the scoring of the hydrogen system building blocks described in this report as well as the local situation of the energy centre assets including:

- Existing equipment and remaining lifespan
- Available space within the energy centre
- Locality of the energy centre, proximity to buildings, opportunities for expansion, vehicular routes and access etc.

Once the preferred pilot project and conversion approach for each of the energy centres has been agreed with Aberdeen City Council and Aberdeen Heat & Power, we will complete techno-economic modelling of the preferred option. This will include the annual modelling of costs, revenues and cost of heat to consumers, and will enable us to identify the gap between today's heat cost and the heat cost with a hydrogen system, indicating the level of subsidy that is required. In addition to the techno-economic modelling, we will develop a definition of the pilot project, a route map for the implementation of the 'Hydrogen for Heat' programme within the DHN and investigate business model options to support the fuel switching.

It is important that any decision to proceed with the pilot project considers the importance of affordable heat to the customers of the heat network and maintains the objective of alleviating fuel poverty. As owners and operators of

the DHN, Aberdeen Heat & Power will ensure that the pilot project aligns with their operational objectives.

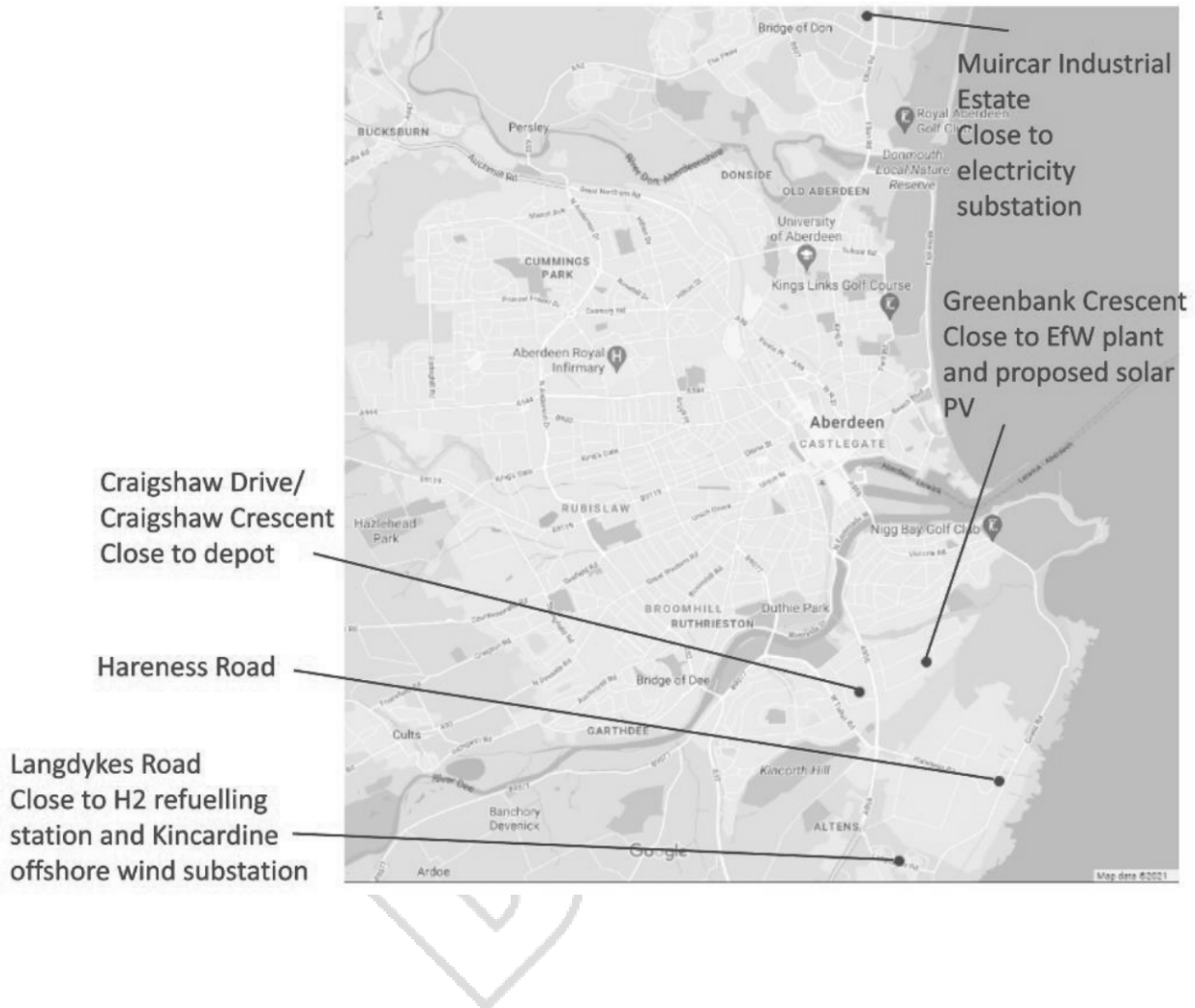
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Appendix A – Proposed hydrogen hub locations



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