Assessing Community Perceptions of Hydrogen as a Fuel for Domestic Heating

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Abstract

The University of Worcester (England) has proposed to install a hydrogen boiler and an air source heat pump on its campus to compare performances of alternative domestic heating solutions. The goal of this project was to assist the University of Worcester (UW), Worcester Bosch, and the Heart of Worcestershire College in assessing public opinion of the UW students and UK residents about the use of hydrogen for domestic heating. In-person open-ended surveys were developed and conducted to document opinions and topics of interest on the use of hydrogen in domestic heating. The data collected provided a clear indication that the Worcester community was ready to accept hydrogen as an energy heating source provided sufficient educational and cost information was available. As a result, educational material was developed based on survey findings and targeted towards the interests of different demographics. In support of this educational material, the team recommended a public education campaign be initiated by using the educational tools developed, and a comprehensive cost analysis of hydrogen technology be performed. Also, the team recommended that the UW pilot project be continued as a means to increase overall acceptance of hydrogen technology and allow for technician training of alternative heating systems.

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Executive Summary

Introduction

As part of the UK's efforts in reduce greenhouse gas emissions, domestic heating has been identified as a significant contributor to carbon emissions. In 2017, domestic heating for space and water contributed to 21% of the nation's total emissions (*Clean Growth – Transforming Heating – Overview of Current Evidence*, n.d.). As a result, decarbonizing domestic heating has become a major focus of UK policymakers. One alternative heating solution being explored is hydrogen-fuelled boilers. Unlike natural gas which produces harmful byproducts like carbon dioxide during combustion, hydrogen only produces water vapour (Clark et al., 2022). Compared to other domestic heating alternatives, hydrogen would be able to use existing natural gas infrastructure for distribution, minimizing costs of integration (Olympios et al., 2022).

The University of Worcester (UW) has proposed to install a hydrogen boiler and an air source heat pump into a demonstration site on the campus. The purpose of this demonstration project will be to compare both systems and to build an educational program for heating technicians from the Heart of Worcestershire College (HOWC) about the maintenance and installation of alternative heating systems.

Goals and Objectives

The goal of the project was to assess public opinion about hydrogen as a fuel for domestic heating. To accomplish this goal, the team identified the following objectives:

1. Research the costs, safety implications, installation process, and heating efficiency of hydrogen boilers.
2. Document current opinions of UW students and UK residents about hydrogen-fuelled boilers for domestic heating.
3. Create suggestions for an educational tool to support the pilot project and provide easily understandable information about hydrogen as an alternative fuel source.

Methodology

Research was first conducted on the costs, source, safety implications, installation process, and heating efficiency of hydrogen boilers. This helped the team gain an understanding of hydrogen boilers enabling the team to have educated conversations with members of the public. A public survey was then distributed in the form of an open-ended in-person survey to residents of the UK and to students on the UW St. John's campus. The survey identified topics of interest and concerns to be included in educational material. Educational resources in the forms of a poster, a trifold pamphlet, and a door hanger were produced, each addressing the five most identified topics of interest based on the survey results.

Findings

Surveys were conducted to assess the opinions of UW students and UK residents on the use hydrogen for domestic heating. The questions covered in the survey asked about respondents' overall opinions of the use of hydrogen for domestic heating, and topics they believed would improve their understanding of hydrogen boilers. The questions were asked in the form of a discussion to allow respondents to share opinions to their desired depth.

Among UK residents, approximately 58% had an overall positive opinion about the use of hydrogen, while only 11% of UW students had a positive opinion. By comparison, 42% of UK residents were neutral toward hydrogen as a fuel source, while 87% of UW students were neutral. The differences in response between the two groups is assumed to be because many students live in accommodations or at home, both locations where they do not have responsibility for or control over their own heating systems.

The most common topics of interest for both UK residents and UW students was cost; followed by safety, sustainability, performance, and a comparison to natural gas boilers. The topics brought up the most by UW students were:

- Cost (53%)
- Comparison between natural gas boilers and hydrogen boilers (47%)
- Sustainability benefits (38%)

The most noted topics of interest to UK residents were:

- Cost (77%)
- Safety (52%)
- Sustainability benefits (49%)

Based on slightly differing topics of interest for residents and students, multiple educational tools were developed tailored to each group. A brochure was developed to contain an overview of information that was easily understandable for a broader audience. A poster was created for the students with a focal point on the overall comparison between natural gas (fossil fuels) and hydrogen gas. A door hanger was created with information that was more relevant to UK residents, the safety and cost were highlighted more to advocate for their interests.

Recommendations

Based on the survey findings, the team recommended that our sponsors begin the following actions as soon as possible:

1. **The UW, HOWC, and Worcester Bosch should launch a public education campaign to spread awareness and accurate information about hydrogen and its applications.**

As identified by the survey data, the people of Worcester, England are generally accepting of hydrogen, provided educational efforts are made. Specifically, this campaign should focus on the following topics of hydrogen: cost, safety, sustainability, performance, and a comparison to natural gas. In the beginning, this campaign will be able to use the material developed from this project, but this campaign would need to be a long-term commitment, meaning updated materials will need to be developed as research is continued.

Additional recommendations include the following:

2. **Worcester Bosch or an independent party should perform a comprehensive cost analysis of hydrogen for consumers.**

The most stated topic of interest for both UW students and UK residents was cost with almost 70% of the total respondents discussing it. This recommended cost analysis should consider initial installation costs, recurring maintenance and gas costs, and indirect infrastructure costs.

3. **The UW, HOWC, and Worcester Bosch should continue with the UW pilot project and use it to further hydrogen heating education for the public as well as heating technicians.**

Through surveying, a recurring observation amongst respondents was a major lack of knowledge about the use of hydrogen as a fuel for domestic heating. With Worcester Bosch and UW as sustainability leaders this UW pilot project can be used as a proof of concept to people that may have concerns and lead to a greater acceptance. This pilot project is planned to serve as an opportunity for technicians to gain proficiency in handling new products and working with hydrogen boilers under controlled conditions.

4. **The UW, HOWC, and Worcester Bosch should promote Worcester, England, as a leading candidate for transitioning to carbon-free alternatives for domestic heating.**

This study provides a baseline to show that many Worcester residents are receptive to hydrogen as an alternative. Providing that the research is continued, and the public is informed, Worcester is an ideal location for a large-scale launch of hydrogen boilers. Using Worcester as a pilot before expanding to the rest of the country will allow the UW trained technicians to work on systems and learn more about hydrogen boiler maintenance while close to home.

Authorship

Section	Primary Author(s)	Reviewer(s)
1.0 Introduction	SO	CD
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2.1 The Need to Reduce Greenhouse Gases	CD	SO
2.2 Hydrogen as an Alternative	EA/SO	CD
2.3 University of Worcester Pilot Project	SO	CD
3.0 Methods		
3.1 Research of Hydrogen Boilers	DJ	CD/SO
3.2 Documenting Public Opinion	CD/SO	ALL
3.3 Development of an Educational Resource	CD	SO
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1.0 Introduction

The UK 2008 Climate Change Act is one of the most ambitious climate policies globally, committing the UK government to reduce national greenhouse gas emissions by 80% before the year 2050 (Lorenzoni & Benson, 2014). Of the current national greenhouse gas emissions, 80% are carbon dioxide (CO_2) (*The Greenhouse Effect - British Geological Survey*, n.d.) and according to a 2017 study, domestic heating for space and water contributes to 21% of the nation's total carbon emissions (*Clean Growth - Transforming Heating - Overview of Current Evidence*, n.d.). This level of CO_2 emissions by domestic heating systems suggests that to reach the goal set by the 2008 Climate Change Act, decarbonization efforts need to be made in domestic heating systems, specifically those that employ natural gas (methane).

Alternative low or zero-carbon heat sources are often focused on electric-powered heat pumps or hydrogen-fuelled boilers (Olympios et al., 2024). Unfortunately, according to Olympios et al. (2022), large-scale heat pump usage in the UK would require major upgrades of electrical systems, including generation, transmission, and storage. Further, for heat pump systems to have a quantifiable impact on carbon emissions, electricity generation and storage must also be carbon neutral (Olympios et al., 2022). In contrast, the initial installation costs of a hydrogen boiler will likely be lower than for a heat pump, as a boiler unit is the only major component of the in-home system that needs to be replaced (Olympios et al., 2022). Much like electrical energy generation, however, hydrogen production would also need to be carbon neutral to have an impact on carbon emissions.

Hydrogen boiler trials have been ongoing for several years, testing if hydrogen is a safe and practical alternative as a fuel for domestic heating. One such trial, H100 Fife, is transforming 300 homes in Fife, Scotland, to be heated by hydrogen boilers using 100% hydrogen gas produced by renewable energy (*About H100 Fife*, n.d.). The process of constructing this new hydrogen network began in May of 2023, concluding in summer of 2025 when the natural gas supply will be switched.

On a smaller scale, the University of Worcester (UW) has proposed to install a hydrogen boiler in a semi-detached home located on the UW St. John's campus. Prior to the installation of the hydrogen boiler, it is important to understand the perceptions and knowledge of campus and Worcester residents. As a result, the goal of this project was to assess community perceptions of hydrogen as a fuel for domestic heating, achieved through conducting research and interviews with UK residents and UW students about hydrogen heating systems.

2.0 Background

In this section, the need to reduce greenhouse gases, why hydrogen is being considered as an alternative fuel, and hydrogen projects in the UK are presented.

2.1 The Need to Reduce Greenhouse Gases

Studies have shown that over the past 50 years, the warming of the earth has primarily been caused by human-induced factors. The US Environmental Protection Agency found that the use of natural gas for electricity and heat production is responsible for about 34% of carbon emissions causing global warming (*Global Greenhouse Gas Overview - U.S. Environmental Protection Agency (EPA)*, 2019). Reducing emissions from domestic heating is an important objective for the UK government and its plan to be net zero by 2050.

UK policymakers instituted the Net Zero Strategy: Build Back Greener policy in 2021 committing the UK to the reduction of carbon emissions from domestic heating. The *Reducing Emissions - Across the Economy* policy aims "to phase out the installation of new and replacement natural gas boilers by 2035" *(3. Reducing Emissions across the Economy - GOV.UK, n.d.*). Since between 85% and 90% of UK homes are heated by natural gas boilers (Olympios et al., 2022) there is a clear need for an alternative heating source.

2.2 Hydrogen as an Alternative Fuel

As shown in Figure 1 below, hydrogen combustion only produces water vapour and heat, eliminating carbon emissions associated with natural gas combustion. If carbon-free methods such as wind, hydro, or solar are used to power electrolysers, hydrogen can be produced and used without releasing any greenhouse gases. The entire process from production to use can be carbon-zero.

$$(1)\ \text{Hydrogen}\ (H_2) + \text{Oxygen}\ (O_2) \xrightarrow{\text{yields}} \text{Water}\ (H_2O) + \text{Energy (heat)}$$

$$(2)\ \text{Methane}\ (CH_4) + \text{Oxygen}\ (O_2) \xrightarrow{\text{yields}} \text{Water}\ (H_2O) + \text{Energy (heat)} + \text{Carbon Dioxide}\ (CO_2)$$

Figure 1: Combustion reactions of hydrogen (1) and natural gas (2)

During incomplete combustion of natural gas (methane), carbon monoxide (CO) gas is also generated, a byproduct known to be colourless, odourless, and toxic. In 2020, CO poisoning was the cause of twenty deaths and 4000 emergency room visits in the UK (Jarman et al., 2023). Switching to hydrogen would not only eliminate CO_2 emissions from boilers, but it would eliminate the risk of death and injuries associated with CO poisoning.

Hydrogen is non-toxic, but in certain concentrations, it can become highly flammable. Fortunately, hydrogen cannot be ignited until concentrations of about 4%, at which point the flame has exceptionally low energy and can only travel upwards. To reach a flammable concentration, a substantial leak would be required in the hydrogen system (T. Collins, personal communication, March 26, 2024). Current plans for the implementation of hydrogen fuel lines into homes would integrate an excess flow meter. If the flow of hydrogen into the house exceeds the expected value, this meter would automatically cut off the supply to the house, preventing a dangerous gas concentration build up. As an added layer of safety, Hy4Heat studies have suggested that the same odorant added to natural gas can and should be used in hydrogen within the home (Murugan, 2020). This scent is already associated with gas by the public and would not require "retraining" for people to identify gas leaks.

Hydrogen Boiler Transition

Based on current UK home natural gas infrastructure standards, up to 83% of British homes can be switched over to hydrogen heating (*A World-First Green Hydrogen Project from SGN | H100 Fife*, n.d). As shown in Figure 2, a hydrogen boiler has the same physical footprint and operational technologies as a natural gas boiler, seen in Figure 3, and can be fitted to the same location in the home.

Since boiler technicians are already familiar with the technologies used in natural gas boilers, minimal training and certification would likely be required for a near-identical hydrogen boiler (T. Collins, personal communication, March 26, 2024). Many of the components of a natural gas boiler heating system such as radiators and pipes would also be able to remain the same. This would reduce system downtime and the required cost and effort for the consumer during the hydrogen transition. To facilitate the transition for consumers, the four major manufacturers of boilers in the UK have all agreed that each of their hydrogen boiler designs will cost the same as their natural gas systems on a volume basis (Merrett, 2021).

Figure 2: Worcester Bosch "Hydrogen Ready" boiler
(Worcester Bosch, 2022)

Figure 3: Worcester Bosch natural gas boiler
(Worcester Bosch, 2019)

Hydrogen Mixtures

The use of hydrogen mixtures or blends is another way to decrease carbon footprints without switching over to a hydrogen boiler. A 20% hydrogen blend can be introduced into the existing gas lines as a blended fuel. Tests conducted by the WEC energy group found that burning a 25% hydrogen blend reduced carbon dioxide emissions by around 10% (*Test Shows Hydrogen*

Blending Slightly Reduces Gas… | Canary Media, n.d.). Many new boilers being produced are labelled as "hydrogen-blend ready" meaning they have been certified to run on a blend of 20% hydrogen and 80% methane. The decrease in emissions provided by a hydrogen blend is not enough to achieve the UK's Net Zero goal alone, but the versatility provided could ease the transition from natural gas to hydrogen while hydrogen infrastructure is built up and adapted.

Hydrogen Projects

One project in Scotland, H100 Fife, uses offshore wind power with the intent of building a 100% green hydrogen network delivering clean energy to 300 households (*A World-First Green Hydrogen Project from SGN | H100 Fife*, n.d.). As seen in Figure 4, after hydrogen is produced through a sustainable electrolysis process, the hydrogen is stored and transported to consumers through a distribution network connected to the homes. H100 Fife estimates the trial will save over 2650 tonnes of CO_2 per year.

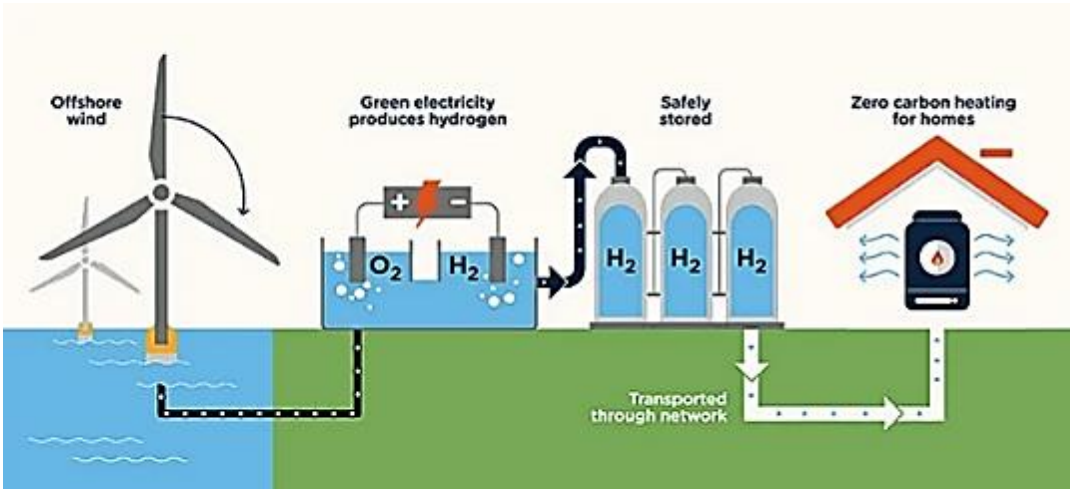

Figure 4: Green Hydrogen Process.
(*Green Hydrogen Is on the Rise*, n.d.)

Hy4Heat is a research programme launched in 2017 and completed in early 2022, funded by the Department for Business, Energy & Industrial Strategy to investigate the feasibility of replacing natural gas with hydrogen. The Hy4Heat programme mission statement was "to establish if it is technically possible, safe and convenient to replace natural gas (methane) with hydrogen in residential and commercial buildings and gas appliances" (*Hy4Heat Final Progress Report*, n.d.). Hy4Heat had two primary objectives: (1) To assess the performance and safety needed to minimise risk associated with hydrogen for heating; and (2) to stimulate the gas industry to conduct performance and safety work on a distribution network for hydrogen (*Hy4Heat Final Progress Report*, n.d.). The research and plans set forth by the project serve as a base for future projects, including the proposed project at the UW.

2.3 University of Worcester Pilot Project

The UW has proposed a demonstration project to compare domestic heating using an air-source heat pump and a hydrogen boiler. This demonstration is proposed to take place in two semi-detached houses on the UW St. John's campus. As seen in Figure 5, these houses are typical UK homes that would accurately represent a family's energy demand during use. In collaboration with Worcester Bosch, UW intends to install a hydrogen-fuelled boiler in one of the houses and an air source heat pump in the other.

These houses are ideal candidates because they are used intermittently as training sites for their respective educational programmes, lowering the heating requirements. It would likely cost UW about £1,600 for a 108.15 m^3 of hydrogen (N4, 99.99%), enough to heat the semi-detached house for the year (April 2024 cost estimate, BOC a Linde Company).

Figure 5: Crime Scene and Ability Houses.

In discussions with Peter Robinson, Vice Principal of Heart of Worcestershire College (HOWC), the UW and HOWC also intend to create a programme to train hydrogen boiler technicians. Through this programme, they propose to teach plumbing and heating technician students from the HOWC about heating systems using future alternative heating sources. The intention of this training is to familiarise future heating system technicians with systems that may soon be publicly available.

3.0 Methods

The goal of this project was to assess the opinions of the UW community and UK residents about hydrogen use in domestic heating. To achieve that goal, three objectives were developed. In this section, we present the methods we proposed to achieve each of the following objectives:

1. Research the costs, safety implications, installation process, and heating efficiency of hydrogen boilers.
2. Document current opinions of university staff and students and Worcester residents about hydrogen-fuelled boilers for domestic heating.
3. Create suggestions for an educational tool to support the pilot project and provide easily understandable information about hydrogen as an alternative fuel source.

3.1 Research on Hydrogen Boilers and Related Topics

To achieve an understanding of hydrogen boilers and related infrastructure, our research focused on the following topics:

1. Hydrogen sources
2. Hydrogen safety
3. Efficiency and byproducts of hydrogen boilers compared to natural gas boilers
4. Infrastructure impacts and adaptation
5. Hydrogen transition expenses

Further knowledge on these topics was gained through an interview with a subject matter expert, Tom Collins, who leads the team at Worcester Bosch developing hydrogen boiler technology. These insights helped informed discussions with the public regarding hydrogen technology. Sample questions from this interview are included in Appendix A.

3.2 Documenting Public Opinion

We proposed to assess opinions on the use of hydrogen and its associated technologies through focus groups and surveys with selected target populations. We defined the study population to include students of the UW, the Technical and Estate staff of the UW, and Worcester residents.

Focus Groups

To identify participants for a focus group, a survey was distributed using promotional posters (Appendix B). These posters contained information about this project, as well as a QR code linked to a Preliminary Screening Survey (Appendix C). This survey was intended to sort interested Worcester community members or students into focus groups. A secondary role of this survey was to filter out responses from people outside of the target population. An additional survey was only distributed to staff members by email to the UW estates team.

We used the following research questions to guide the development of focus group and interview questions:

1. What are the selected populations' perceptions about hydrogen boilers for heating?
2. What do the selected populations know or believe to know about hydrogen boilers for heating?

We proposed a focus group design of six to ten participants and two facilitators. The focus group was to be semi-structured with a list of topics and questions that were to be used to facilitate a conversation. Sample questions are included in Appendix D.

Post Focus Group Survey

Following the focus group with staff members, we planned to ask the participants to complete the post-focus group survey found in Appendix E. Participants were to be prompted to articulate changes to their perspectives and understanding regarding hydrogen heating following the focus group discussion. Further, we intended to ask if there were any topics that they believed required further clarification.

In Person Survey

We used an in-person open-ended survey adapted from the focus group questions (Appendix F) to assess public concerns and knowledge relating to hydrogen use. This type of survey was used to avoid data contamination and collect non-partisan opinions about hydrogen boilers. We conducted this survey at popular public locations, such as pubs and coffee shops near Worcester High Street and the UW campus. These locations allowed for diverse backgrounds of respondents and allowed for multiple surveys to be conducted in a timely manner. We were able to return to the same locations multiple times during the day to collect more interview data without repeating respondents.

Each survey was intended to last about 5 minutes, but for those who were interested, more in-depth conversations could be carried out. During each survey, detailed notes were taken of participant responses, both prompted and unprompted, as well as observations of demographics such as age range and presenting gender.

Similar surveys were conducted with students on the UW campus. The background information supplied, and the questions asked were the same for both the students and UK residents, however, students were offered incentives for their participation. Following their completion of the survey, students were allowed to spin a wheel to determine what kind of incentive they would get, ranging from mini chocolate bars to £4 drink vouchers redeemable on campus.

3.3 Development of an Educational Resource

As a tool for educating the communities surrounding the UW, we proposed to develop several resources that can be used to spread awareness and knowledge about hydrogen-fuelled boilers. These resources were to be developed using information gained from survey results to educate the public. The educational tool is to provide an easily readable resource for people with little or no knowledge or background in subjects like hydrogen or natural gas heating systems. It was also proposed that the tools would include graphics to visually depict the comparisons made to natural gas boilers that many people are already familiar with.

4.0 Results

4.1 Research Findings

This section will provide a summary of the findings from the following research topics:

1. Hydrogen sources
2. Hydrogen safety
3. Efficiency and byproducts of hydrogen boilers compared to natural gas boilers
4. Infrastructure impacts and adaptation
5. Hydrogen transition expenses

Hydrogen Sources

Hydrogen is commonly categorised into a wide colour band based on the method used to produce the gas, as seen in Figure 6 below. The typical colours discussed the most for large-scale sustainable production are blue and green. A more extensive explanation of hydrogen sources and infrastructure is included in Appendix G.

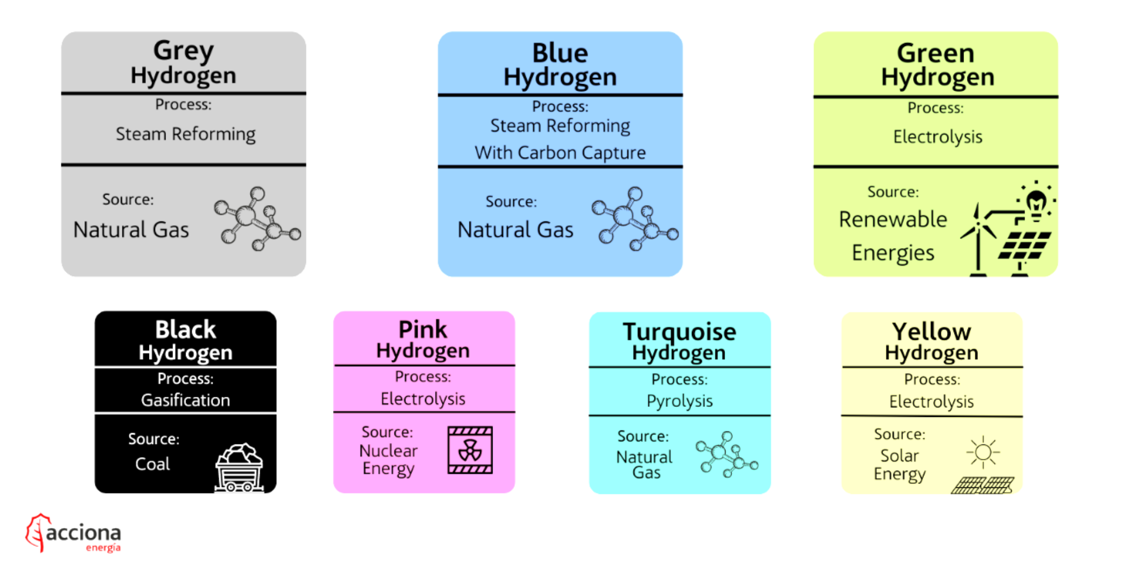

Figure 6: Colour chart of hydrogen

(*What Are The Colours Of Hydrogen And What Do They Mean?*, 2022)

Blue hydrogen is hydrogen produced using processes that traditionally generate carbon emissions but utilise carbon capture and storage (CCS) technology to offset the carbon output. The most common process used is called steam methane reformation (SMR) where methane is reacted with steam and a catalyst to form hydrogen (*Hydrogen Production: Natural Gas Reforming | Department of Energy*, n.d.). Many SMR facilities in the UK can incorporate CCS technologies with efficiencies estimated to be 90% (*Hydrogen Analytical Annex*, 2021); but concerns still exist with blue hydrogen because of its continued dependence on fossil fuels and carbon emissions. Despite concerns, SMR accounts for more than 75% of hydrogen production in the UK (*Hydrogen Analytical Annex*, 2021). Incorporating carbon capture technology into existing facilities can provide a promising path for producing low-carbon emission hydrogen while zero-carbon production infrastructure is being developed (Mohammed et al., 2024).

Green hydrogen is produced using a process called electrolysis that is powered by renewable energy sources. Electrolysis uses electricity to split water into its components, hydrogen, and oxygen. When the electricity used in electrolysis is generated from renewable energy, the entire process has zero carbon emissions. Electrolysis is currently limited, with costs at approximately 5.30 £/kg for production, and an efficiency from 67-84% (Safe, 2023). In comparison SMR costs approximately 1.17 £/kg and has an efficiency of 70–85% (Farhana et al., 2024). With the development of materials and processes used in electrolysers, efficiency and cost are looking to improve with high-performance electrolysis cells (*Our Company – Hysata*, n.d.).

Hydrogen Safety

Hydrogen is often perceived as a dangerous and explosive gas. Compared to natural gas (methane) and gasoline (petrol), hydrogen has a much wider flammability range[1] in air. Further described in the third row of Table 1, the ignition energy[2] of hydrogen is shown to be 1/10th of that of gasoline and nearly 1/15th of that of natural gas. This indicates that hydrogen is easier to ignite, however, this energy is measured at the stoichiometric mixture[3], which is a significantly higher concentration for hydrogen than gasoline or natural gas. In the case of a leak, a much larger leak would be required for hydrogen to reach its stoichiometric mixture than natural gas or gasoline. At concentrations closer to the lower flammability limit, more comparable to a gas leak within the home, the ignition energy of hydrogen is comparable to methane or gasoline (*Hydrogen Safety - Fact Sheet Series*, n.d.). Hydrogen also has a comparably wide range of explosion concentrations[4] in air, meaning there is a wider range of hydrogen concentrations where there is a risk of explosion. However, the lower explosion concentration of hydrogen is considerably higher than natural gas and gasoline, meaning it takes longer for hydrogen to build up to the concentration needed before an explosion is possible.

Table 1: Flammability characteristics of hydrogen and other common fuels
(Adapted from *Hydrogen Safety - Fact Sheet Series*, n.d.)

	Hydrogen	**Gasoline**	**Methane**
Flammability Concentration Limits (in air)	4 - 74%	1.4 - 7.6%	5.3 - 15%
Explosion Concentration Limits (in air)	18.3 - 59.0%	1.1 - 3.3%	5.7 - 14%
Ignition Energy (mJ)	0.02	0.20	0.29
Flame temperature in air (C)	2045	2197	1875
Stoichiometric Concentration Mixture (most easily ignited in air)	29%	2%	9%

[1] Flammability Range: The range of concentrations at which a gas is flammable.
[2] Ignition energy: The energy required to ignite a gas mixture.
[3] Stoichiometric mixture: The "optimal" concentration of a gas for combustion. There is no deficiency or excess gas. Gas is also most easily ignited at this concentration.
[4] Explosion Concentrations: The range of concentrations at which a gas is explosive.

Another safety consideration is diffusivity, or the ability to disperse into a non-flammable concentration. The diffusivity of hydrogen is about 3.8 times faster than natural gas, making it difficult for hydrogen to accumulate to flammable or explosive concentrations (*Hydrogen Safety - Fact Sheet Series*, n.d.). Integration of excess flow meters to houses using hydrogen would alleviate the risk of hydrogen build up within the home. Following detection, this device would cut off the hydrogen flow into the house, preventing further build up and allowing for the hydrogen gas to disperse.

Byproduct and Efficiency Comparison with Natural Gas

The main byproduct of hydrogen combustion is water vapour, although when burning in air, other byproducts like nitrogen oxides (NOx) can be produced. NOx refers to nitric oxide (NO) and nitrogen dioxide (NO_2), neither of which are considered greenhouse gases. When these gases are released into the atmosphere, NOx can mix with precipitation to form acid rain that can be harmful to ecosystems.

Both hydrogen and natural gas boilers form NOx, but current prototype hydrogen boilers are estimated to produce less than 25 mg of NOx per kWh of energy (T. Collins, personal communication, April 9, 2024) compared to natural gas boilers that currently release between 25 - 50 mg of NOx per kWh of energy (Venfield & Brown, 2018). For readers interested in nitrous oxide production during hydrogen combustion refer to *Nitrous Oxide Emissions Associated with 100% Hydrogen Boilers: Research* for more information.

It is important to note that nitrogen oxides are easily confused with the potent greenhouse gas, nitrous oxide (N_2O). The overall emissions of natural gas is equivalent to 210-230 grams of CO_2 per kWh of energy (*Carbon Footprint of Heat Generation*, 2016). In contrast, hydrogen boilers produce the equivalent of 0.07 grams of CO_2 per kWh of energy in N_2O, 3000 times lower than the total emissions of a natural gas boiler (*Nitrous Oxide Emissions Associated with 100% Hydrogen Boilers: Research*, 2023). Hydrogen lead at Worcester Bosch Home Comfort stated that, "Gas boilers were already very, very small producers of NOx, hydrogen is an ultra-low producer of NOx and a real opportunity to clean up the gas quality in our towns" (*Interview: Tom Collins, Hydrogen Lead at Worcester Bosch, Bosch Home Comfort, 2021*).

The typical natural gas boiler has an efficiency of around 94-95% (*Boiler Efficiency - an Overview | ScienceDirect Topics*, n.d.), while hydrogen-fuelled boilers are estimated to be approximately 1.8% less efficient than natural gas boilers (T. Collins, personal communication, April 16, 2024). Over time hydrogen boiler technology could advance to be equally as efficient as natural gas boilers.

Infrastructure Impact

A unique characteristic that makes transporting hydrogen difficult is a phenomenon called hydrogen embrittlement where metals in contact with hydrogen for extended periods become brittle at increased rates. This phenomenon is intensified by increased pressure, such as pressurised hydrogen in a tank or a pipe. In a research paper by Murakami, observed crack growth rates in containers storing hydrogen were 30 times higher than those that did not contain hydrogen (Murakami, 2019). Many of the pipes currently used for natural gas distribution in the UK are made of degradable materials like iron or steel. The UK government has been replacing the iron and steel pipes since the 1980s with polyethylene (plastic) pipes that are not as susceptible to hydrogen embrittlement. If all existing pipelines were converted to or coated with polyurethane, the gas grid would be mostly compatible with hydrogen (Dodds & Demoullin, 2013).

Cost

Due to developing technology, a precise cost estimate is currently unknown. The four major producers of hydrogen boilers projected the costs of hydrogen boiler units to be a comparable price to current natural gas boiler units (Merrett, 2021).

The reusability of radiators and pipes within a house minimises costs for homeowners when installing the new boiler unit. Projected costs for hydrogen gas show increased gas prices in the beginning, typical for emerging technologies. When hydrogen infrastructure is better established, experts believe the price is likely to be reduced over time as the technology becomes more widespread (T. Collins, personal communication, March 26, 2024). With the increasing price of natural gas, there is potential for prices at the transition time to be comparable between the two gases.

4.2 Focus Groups

Focus groups were an intended component of this project using the sample questions seen in Appendix D. These focus group questions were developed to encourage conversation and obtain in-depth opinions rather than surface-level answers.

Worcester Public

To identify participants for focus groups, we designed several promotional posters. These posters were used to attract attention and direct interested viewers to the Preliminary Screening Survey (Appendix C). Using the data from the survey, respondents would be filtered by the desired target populations, and further by their interest in a focus group. The posters were then distributed to ten different public locations around the UW, including pubs, pharmacies, petrol stations, and grocery stores. Many posters were in locations with high traffic volume, while others were posted in waiting spaces where people are might more easily take interest in a poster.

Following distribution of the posters, responses were minimal. In the first two weeks of the posters being up, there were only two interested responses. Ultimately, due to this low response, we were unable to identify enough participants for a focus group. At that time, it was determined that focus groups would not be possible, and thus our attention was shifted to prioritizing in-person open-ended surveys.

In an effort to gain data from the respondents interested in a focus group, emails were sent offering to conduct a phone interview using the questions from the open-ended survey (Appendix F) in place of a focus group. While several respondents expressed interest in a phone interview, none followed through.

One design feature of the posters was "tear-off" tabs at the bottom of the page. This allowed people that were interested to take information about the focus group with them and fill out the interest survey later. Interestingly, upon returning to poster locations, many posters were missing many, sometimes all, of the tabs despite our lack of responses. This may indicate that many people that saw the posters were interested in participating; however, instead of filling out the survey in the moment, they may have forgotten about it, or ultimately decided that they weren't interested. In this sense, it is possible that the tabs prevented interested members in the public from filling out the survey.

Staff

Similarly to the public, an electronic survey was to be used to identify respondents for focus groups. This survey was to be forwarded to the estates staff directly via email, however, upon contact with the Director of Estates, this was determined to be impossible. Due to the timing of the distribution of the survey, it would have been impossible to form, schedule, conduct, and analyse data from focus groups prior to our departure from the project site. Ultimately, the estates team were never contacted with the interest survey.

4.3 UW Student and Worcester Public Opinion Survey

This section summarises the findings from in-person surveys with UW students and UK residents in Worcester, England[5]. The questions asked were:

1. How familiar are you with home-heating systems?
2. If we told you this room was heated by hydrogen, what would your thoughts be?
3. Would you ever consider using hydrogen-based heating in your home?
4. What topics do you believe would be helpful in understanding prior to the installation of a hydrogen boiler?
5. Would you say you have an overall positive, negative, or neutral opinion on hydrogen for domestic heating?

The questions posed by the survey were created to apply to anybody in the UK by referring to a hydrogen heating project in general, rather than the UW project specifically.

Q1: Familiarity With Home Heating

To classify respondents' reported familiarity, four categories were created as described in Table 2. When asked, participants described their familiarity and knowledge level of home heating systems, and their responses were used to sort them into one of the categories. These categories were then used to quantify the respondents' self-perceived knowledge level.

[5] This project aimed to assess opinions of UK residents; however, the survey was only distributed in Worcester, England. The results presented here may not be representative of the wider UK population but did include some responses of residents from outside Worcester, England.

Table 2: Familiarity Level Categories

Category	**Description**
Not familiar	No knowledge of heating systems spanning beyond base function.
A little familiar	Some knowledge about heating system components: how they work together, and alternatives.
Somewhat familiar	Average knowledge about heating system components: how they work together, and alternatives.
Very familiar	Above-average knowledge about heating system components: how they work together, and alternatives.

As shown in Figure 7, most of the surveyed UK residents considered themselves to be in some way familiar with natural gas home heating systems, with only about 21% stating that they are not at all familiar. The familiarity level is similar to a normal distribution with the most resident survey respondents claiming to be "somewhat familiar." By contrast, UW students had a different distribution, where most respondents, about 57%, claimed to be not at all familiar, and another 34% claimed to be "somewhat familiar." Interestingly, no students claimed to be "very familiar" with domestic heating systems.

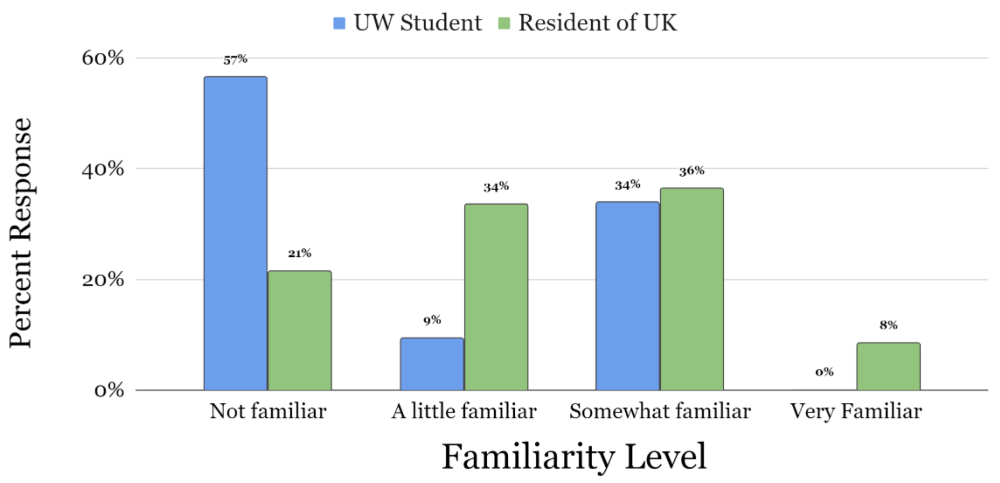

Figure 7: Familiarity distributions of UW students and UK residents

$n_{Student} = 53$, $n_{Resident} = 107$

One reason for the student distribution favouring the "not familiar" could be that many students are likely living in locations where they are not forced to interact with their heating system: in student accommodation or at home. In both cases, the maintenance, cost, and use of the heating system components is not the student's responsibility. This disconnect from students own heating systems can be a contributor to the knowledge difference between students and general UK residents who likely rent or own their own home and are personally responsible for paying heating costs.

Interestingly, men claimed to be more familiar with heating technology than women, as seen in Figure 8. The men's population appeared to follow a similar distribution to a typical normal distribution like the overall UK residents, but the women followed a right skewed distribution. In these distributions, men considered themselves “somewhat familiar” most often, while women considered themselves “not familiar” most often.

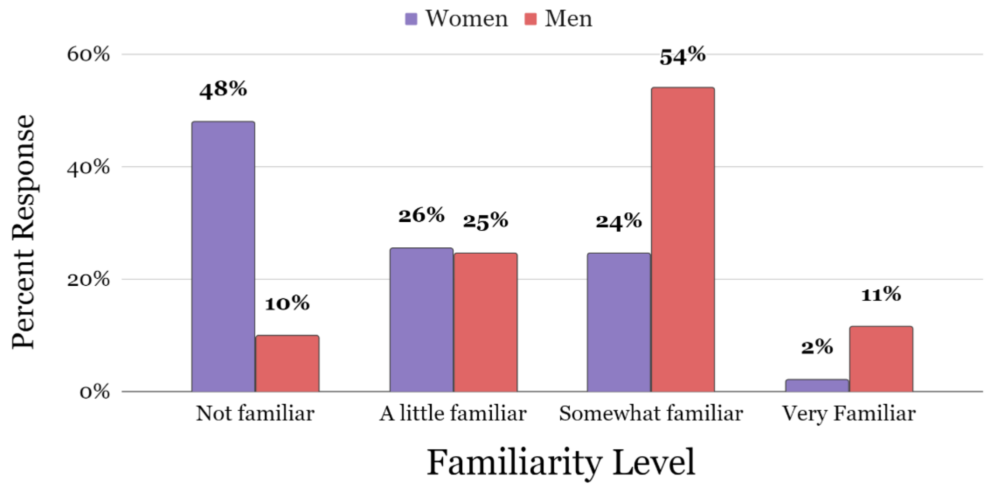

Figure 8: Familiarity distributions of women and men

$n_{Women} = 96$, $n_{Men} = 61$

While the topic of this question is not directly targeted to public perceptions of hydrogen, an understanding of heating systems in general may help in perception of the similarity between hydrogen and natural gas fuelled systems. We also believe this question provided a suitable introduction to the following questions to encourage a two-way discussion. We were able to curate the language we used in the following questions based on familiarity.

Q3: Consideration of Hydrogen-Based Heating

When asked about whether they would consider hydrogen for use in their home, about 88% of UK resident respondents reported that they would as shown in Figure 9. Many of the people that responded “yes” also noted that they would be inclined to pay the anticipated premium for hydrogen if there is a justification, for example, hydrogen being better for the environment, safer, or more efficient. Most respondents had never previously considered using hydrogen as an alternative to natural gas boilers due to a lack of information provided to them, but many of the same people responded that they would consider it for the future. A small number of respondents also attributed their decision of “unsure” or “no” to their home currently already utilising low or zero carbon heating, such as heat pumps. For these people, transitioning to a hydrogen fuelled boiler system would not make sense.

Due to the wording of the question, we believe some respondents misunderstood its meaning, making their responses potentially inaccurate. Some respondents may have understood the question to be “would you accept a hydrogen boiler in your home right now?” Several respondents, approximately 6%, stated they would not consider hydrogen boilers in their homes. A portion of these respondents attributed this decision to recently replacing their boiler with a new natural gas boiler. Due to the financial burden of a new boiler, these respondents would not consider renovating their current heating system. This explanation, though, would not stop respondents from considering hydrogen boilers in the future as our question intended to ask about.

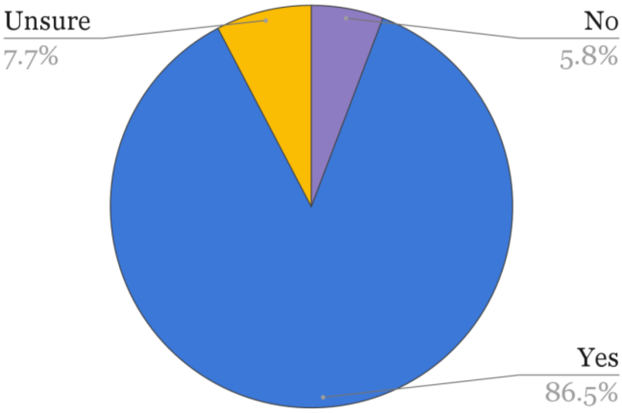

Figure 9: UK resident's willingness to consider hydrogen boilers for heating their home

n = 104

Similarly to the UK residents that were surveyed, student respondents also largely said they would consider hydrogen boilers for their future, although to a lesser extent, 66%. The UW students also made the note that they would consider a hydrogen boiler provided there was a benefit like a decreased cost. Like the UK resident's results, some of this may come from misunderstandings in the question. Many more students responded unsure, and many attributed this to not having control over their heating systems. In comparison to UK resident results, a greater portion of students responded that they would not consider hydrogen for their homes, roughly 9%.

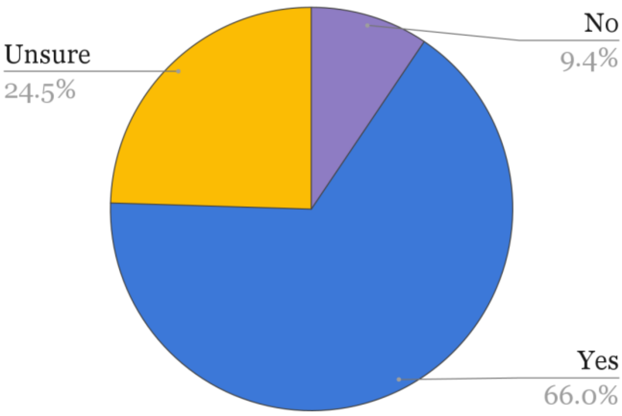

Figure 10: UW student's willingness to consider hydrogen boilers for heating their home

n = 53

Q2 & Q4: Topics of Interest for Understanding Hydrogen

Respondents were asked the hypothetical question "*How would you feel if this room was heated by a hydrogen boiler as opposed to a natural gas boiler?*" This question was intended to discover initial concerns of being around hydrogen gas, however, for many, there were no immediate concerns. Most responded that they would not be bothered as long as it was warm and safe. In this study, no respondents in either the UK resident or UW student groups expressed strong positive or negative opinions. A handful of respondents jokingly gave the response "As long as it doesn't blow my house up." Although the statement was delivered as a light-hearted joke, many of these participants also mentioned safety as a topic of interest.

In the other question about topics of interest, "*What topics do you believe would be helpful in understanding prior to the installation of a hydrogen boiler?*", various answers were given, although many shared the same topics. When compiling survey results from questions 2 and 4, the topics identified by participants were organised into ten categories used to quantify which topics were discussed the most. The categories are defined below in Table 3.

Table 3: Interest Topics Identified by the Survey

Topic	**Description**
Cost	Overall cost of transition to hydrogen boilers including parts, labour, safety technology, hydrogen gas, and infrastructure.
Legislation	How the government will implement a hydrogen network and hydrogen related taxes.
Maintenance	The maintenance requirements and costs of hydrogen compared to natural gas.
Overall Comparison	Pros and cons between hydrogen boilers and other heating systems.
Performance	How the efficiency and energy output of hydrogen compares to natural gas.
Safety	How the safety of hydrogen compares to natural gas.
Source	Methods of hydrogen production.
Storage	How hydrogen will be temporarily stored when not in use.
Sustainability	The sustainability benefits of hydrogen relating to net carbon output and environmental impacts.
Transport	How hydrogen will be transported from production and storage to homes.

To identify additional concerns, respondents were able to list as many topics of interest that they had. Some respondents only listed one topic, while others listed as many as five. As seen in Figure 11, the topic mentioned most by UK residents was cost, with approximately 77% of participants reporting it as something they would like to know more about. Other high-interest topics include safety (52%), sustainability (49%), and performance (36%).

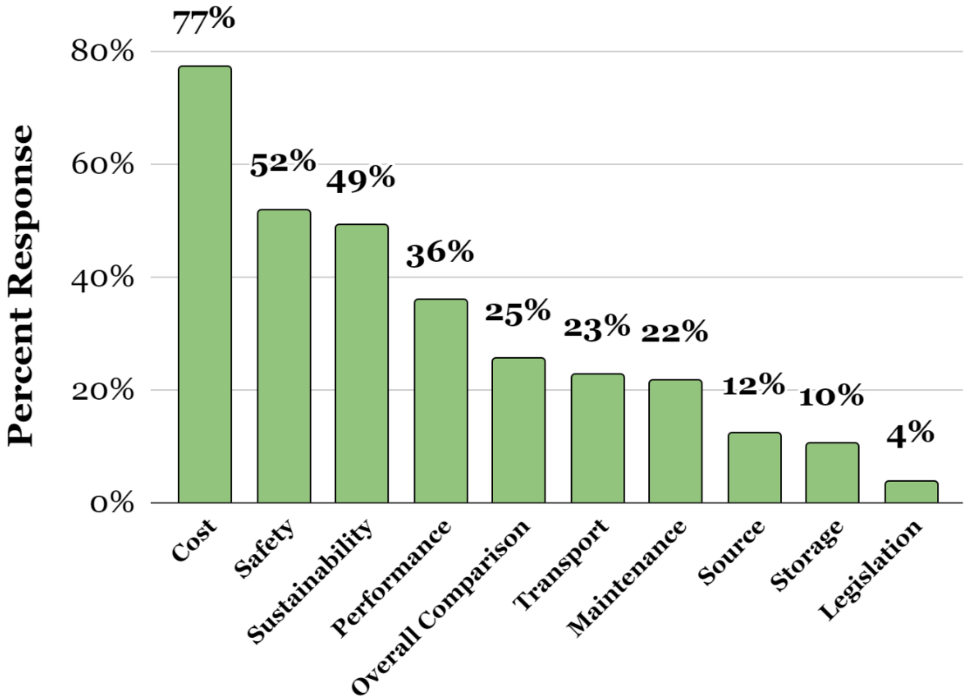

Figure 11: Distribution of interest topics of UK residents

n = 106

As seen in Figure 12, the topics of interest of UW students were slightly different than those of UK residents. The topic mentioned most by UW students, similar to UK residents sampled, was cost, with approximately 53% of participants reporting it as something they would like to know more about. Other high-interest topics include overall comparison (47%), sustainability (38%), and safety (34%).

Overall, students seemed to have a lower understanding of both natural gas and hydrogen boilers, which led to an increase in interest in an overall comparison. Many students expressed that they possess very little knowledge of both hydrogen and natural gas and wanted a list of pros and cons for each fuel. One potential reason for this is that many of the UK resident sample population were generally aware of the sustainability benefits of hydrogen, whereas the students did not have the same understanding of why hydrogen is being considered.

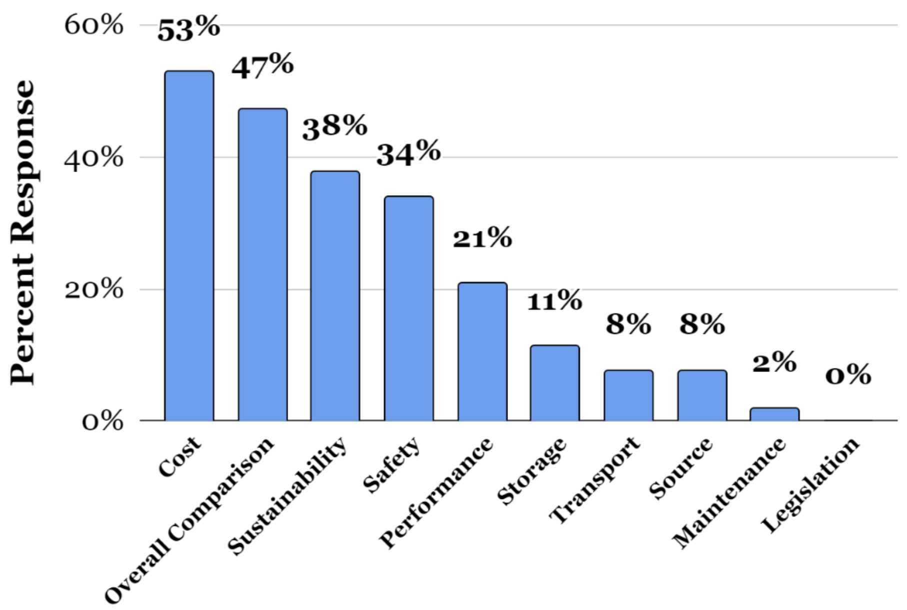

Figure 12: Distribution of interest topics of UW students

n = 53

Noticeably, UW students were less likely than UK residents to respond with multiple topics of interest. This is shown by the lower average number of topics of interest. The UW students responded with an average of 2.21 concerns per respondent compared to 3.11 concerns per respondent found with UK residents. It is unclear what the cause of this is, but one possible explanation is inconsistency with the in-person survey delivery. It is possible that some students did not think they were allowed to respond with multiple topics. This is unlikely to be the case, though, because it was calculated that about 71% of the UW students responded with two or more concerns. While this is lower than that of UK residents, about 94%, a significant number of students responded with more than two concerns, indicating that most students were aware that they were able to. Another explanation is that students are generally less concerned due to the belief that they do not have a part in the decision to switch to hydrogen. The UW students have never been in situations where they have been responsible for the heating in their home. Due to this, they are unaware of the topics and risks associated with home heating systems.

Q5: Overall Opinions of Hydrogen for Domestic Heating

When asked to rate their overall opinion of hydrogen for domestic heating, respondents were given the option between "Negative," "Neutral," or "Positive." As seen in Figures 13 and 14 below, students were far more likely than UK residents to respond "neutral". Many UK resident respondents understood hydrogen to be more sustainable and environmentally friendly than natural gas and were more inclined to respond "positive." Many of the neutral responses were attributed to a lack of information about the benefits or risks of using hydrogen. As noted previously, many UW students lack an understanding of hydrogen and did not possess enough information to form a positive or negative opinion. The only respondents who formed an opinion were those who believed to have knowledge prior to the survey. Out of 160 respondents, only one had a negative opinion about hydrogen, explaining that they believed hydrogen was dangerous.

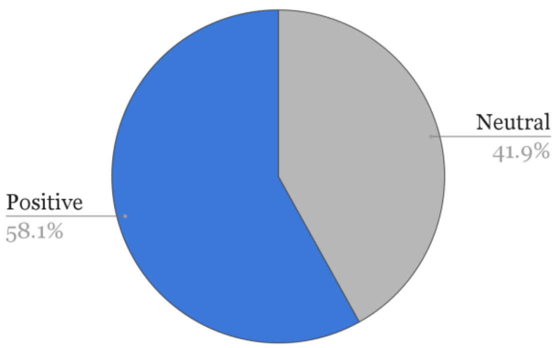

Figure 13: UK resident overall opinions

n = 107

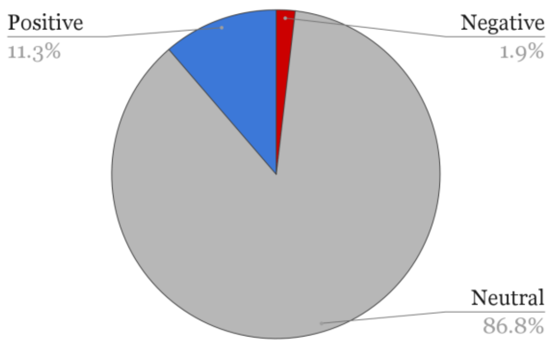

Figure 14: UW student overall opinions

n = 53

Observational Data During Interviews

When interviewing UW students, many had unsure opinions due to their lack of understanding of the subject. Some UW students in separate groups had a major misconception: that natural gas was "natural" and was therefore better for the environment than alternative fuels like hydrogen. Later in the discussion, many of these same students still said they would consider using a hydrogen boiler in their homes because they believed it would be more environmentally sustainable. This response was unlikely to be prompted by interviewers because no information on the subject was given until after the data was collected. These conflicting responses may further indicate that much of the UW student population does not know why hydrogen is being considered.

4.4 Educational Resource

During our public survey, certain demographic groups identified slightly differing topics of interest. Both UK residents and UW students identified cost, safety, sustainability, performance, and overall comparison as their top five topics of interest, but they were prioritised in a different order. Using these topics, we used our research from section 4.1 to simplify the information into Table 4. This table was used as a quick reference for comparing hydrogen and natural gas when developing the materials. Importantly, cost is not listed as a topic in the table. This is because we were unable to get consistent estimations. There are a lot of elements that will play into the overall cost for the consumer, and it was decided that the steps for an in-depth cost analysis would be to out of the scope of this project. Although overall costs are difficult to quantify, several sources consistently stated that initial installation cost will likely be similar to a natural gas boiler, so this was included as a cost note in the materials.

One note is that methane is being referred to as "fossil fuels" rather than "natural gas" throughout all the materials to avoid the misinterpretation of the word "natural" as described by our observations from the public survey in section 4.3.

Table 4: General comparison between fossil fuel gas and hydrogen gas

	Aspect	**Methane**	**Hydrogen**
Safety	Flammability	Highly flammable	Highly flammable
	Leakage	Can leak and be ignited	Can leak and be ignited
	Combustion	Natural gas + Oxygen = Water + Heat + Carbon Dioxide	Hydrogen + Oxygen = Water + Heat
	Incomplete Combustion	Results in toxic carbon monoxide that can cause acute toxicity when flue gas is mismanaged	Does not occur
Performance	Energy Density	Moderate energy density (per unit volume)	Low energy density (per unit volume)
Infrastructure	Availability	Abundant	Abundant
	Distribution	Well-established system	Limited existing delivery systems
	Storage	Stored in tanks or underground storage facilities	Can be stored underground in existing gas stores or in tanks in both liquid and gaseous forms using specialized materials
	Production	Dependency on fossil fuel extraction	Uses electricity to split water
	Other Notes	None	Can weaken materials used in storage and transportation (embrittlement)
Sustainability	Environmental Impact	Methane is a potent greenhouse gas, contributing significantly to climate change	When produced through renewable energy can be 100% environmentally friendly

For educational resources a simplified graphic was developed (Figure 15) to show a comparison between fossil fuel and hydrogen combustion.

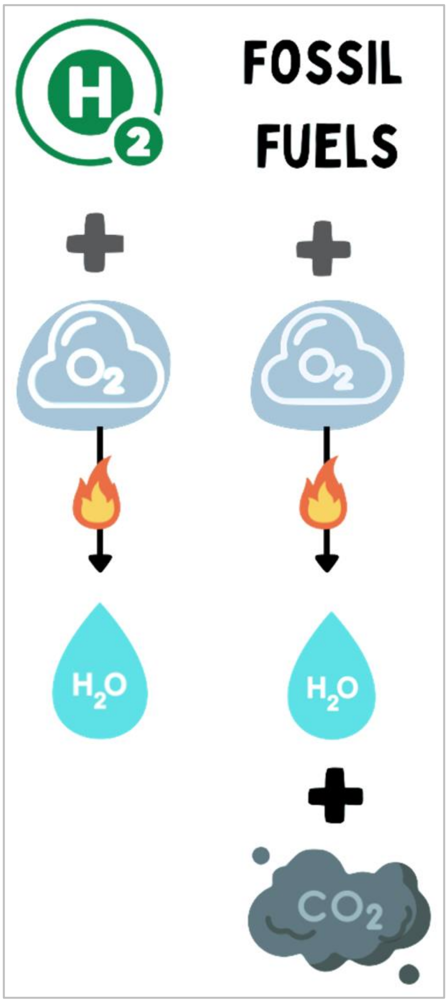

Figure 15: Graphic depicting a comparison between hydrogen and fossil fuel combustion

Since the top five concerns were similar between groups, a brochure applicable to both populations were developed, shown in Appendix I. A brochure was chosen as a broad outreach approach because it is easily distributable in public locations and has space to cover a broad range of topics. This brochure covers the five greatest topics of interest determined in our public survey, cost, safety, performance, and a comparison to natural gas boilers. Additionally, the brochure had a brief section about how a boiler works to address the lack of boiler knowledge found, specifically in the student population.

For residents of Worcester, we opted for a direct approach using a door hanger, seen in Appendix J. Much of this information was the same for this mode of distribution, but the general information about how a boiler works was left out. We found that UK residents were more knowledgeable about home heating systems than students, so we found the inclusion of this content unnecessary. This was also to save space on the smaller form factor of the door hanger.

For the student population, we decided to create a poster to be placed around campus, seen in Appendix K. In discussion with our sponsor, Katy Boom, we learned that some student organizations have shown success in outreach using posters posted in locations that are well trafficked locations or locations where students are not preoccupied, for example in the cafeteria or in restrooms. This poster also contained much of the same information as the brochures, but they had a greater focus on general boiler information and the comparisons between hydrogen and natural gas as a fuel.

One potential limitation of all these modes of outreach is that they rely on someone to be interested by the topic to spend the time to read the information. All modes developed used a bright blue background and eye-catching graphics to grab the user's attention. Further, by focusing the content on sustainability, we hoped to attract and retain a reader's attention. This is further aided on the brochures by using the rhetorical question, "Are you hydrogen ready?" By using this question, we believe that people will be curious about what the question means and will read further to learn more about it.

After the materials were drafted, all were shared with the project sponsors as an opportunity to receive feedback on formatting, content, and accessibility. These materials were developed using Canva, an online graphic design tool. On Canva, we used a tool that checks accessibility for individuals with vision impairments. This helped with reducing low-contrast text and typography issues.

4.5 Other Challenges in Data Collection

Surveying members of the public came with its challenges. One major challenge was finding establishments to interview patrons in. While many owners and managers were happy to let us interview their patrons, certain locations did not have willing participants for our survey.

Another challenge was the time constraint imposed by this project. Of the eight weeks we had on-site to research, UW students and staff were on Easter holiday for two. For a project that is focused heavily on the University population, this disrupted data collection. Because of this factor and our need to restructure our methods on-site, we were forced to put off data collection until past the halfway point through the eight-week period.

5.0 Recommendations

The recommendations described below include short and long-term recommendations for advancing public and government perception of hydrogen. Also included are specific recommendations about public outreach for future student projects.

5.1 Short Term Recommendations

We advocate for the immediate action of our short-term recommendations. They will emphasise a critical role in advancing the adaptation of hydrogen technologies.

1. **The UW, HOWC, and Worcester Bosch should launch a public education campaign to spread awareness and accurate information about hydrogen and its applications.**

As revealed by our research, knowledge gaps about hydrogen boilers have an impact on the public's opinion. Various outreach methods should be used such as social media, community workshops, and informational brochures to reach a wide audience. This includes the immediate implementation of the educational materials developed for the purpose of this project. As found in this study, passive outreach methods like posters do not engage the community well. Because of this, we encourage an active outreach approach like engaging in discussion with members of the community in a public setting. The campaign should address the topics identified by our research including but not limited to:

- Estimated cost figures,
- A general comparison of hydrogen boilers to natural gas boilers, and
- Safety facts

During this information dissemination campaign, it is important to also address hydrogen risks to present impartial data. The sources of included statistics should also be provided to encourage viewers to conduct their own research using scholarly sources. Finally, this campaign should not use the phrase "natural gas" and should instead opt for terms like "fossil fuels" to prevent the misconceptions of the word "natural."

2. **The UW, HOWC, and Worcester Bosch should create a website or blog post that is constantly revised with hydrogen research as well as updates on hydrogen projects.**

Because of ongoing research and many uncertainties related to hydrogen integration, it is important to develop a method for keeping the public informed and updated regularly. This website should be integrated with a public education campaign, highlighting the same topics identified above. While a public education campaign should focus on outreach to the public and spreading awareness, this website should be used to support the outreach by providing something for interested individuals to refer to. One example of what this website should look at is the NREL Solar Energy Basics web page. Similar to the education campaign, the promotors of this website should be aware of bias of presenting research material from a pro-hydrogen source. One thing to consider would be partnering with non-profit organisations to host and maintain the website.

5.2 Mid Term Recommendations

Mid-term recommendations are those we identify as not feasible at the time of publication of this report but should be addressed once possible.

3. **Worcester Bosch or, an independent research organization, should perform a comprehensive cost analysis of hydrogen for consumers.**

As noted in section 4.3, the most stated topic of interest for both UW students and UK residents was cost with over half of our respondents discussing it. Because hydrogen is still an emerging technology, many aspects of hydrogen implementation are not fully understood or determined. Because of these constantly changing aspects, it is difficult to accurately determine a cost estimate for the consumer. This recommended cost analysis should consider initial installation costs, recurring maintenance and gas costs, and indirect infrastructure costs.

5.3 Long Term Recommendations

Long term recommendations are those that we perceive as feasible upon the completion of the foundational steps.

4. **The UW, HOWC, and Worcester Bosch should continue with the UW pilot project and use it to further hydrogen heating education for the public as well as heating technicians.**

The UW pilot project can be a valuable testing location for modern technologies and provide learning opportunities for both technicians and the public. In our surveying, a recurring observation amongst respondents was a major lack of knowledge about the use of hydrogen as a fuel for domestic heating. With Worcester Bosch and UW as sustainability leaders this UW pilot project can be used as a proof of concept to people that may have concerns and lead to a greater acceptance. This pilot project is planned to serve as an opportunity for technicians to gain proficiency in handling new products and working with hydrogen boilers under controlled conditions. This program with the HOWC and UW will be aided in its proximity to Worcester Bosch and can provide a basis for similar programs as they are required when hydrogen is widely used in the future.

5. **The UW, HOWC, and Worcester Bosch should promote Worcester, England, as leaders for transitioning to hydrogen to achieve net zero carbon emissions caused by domestic heating.**

This study provides a baseline to show that many Worcester residents are receptive to hydrogen as an alternative. Providing that the research is done, and the public is informed, Worcester displays as a prime location for a large-scale launch of hydrogen boilers. Also supporting this, one of the leading developers and manufacturers of hydrogen heating, Worcester Bosch, is in the city. Using Worcester as a pilot before expanding to the rest of the country will allow the Worcester Bosch technicians to work out any concerns or struggles while close to home.

5.4 Recommendations for Managing Future Student Projects

These recommendations are targeted to future student projects conducted on this subject. We believe consideration of these recommendations will prevent future projects from encountering some of the challenges we endured.

6. **Student research projects should utilise active outreach methods rather than passive outreach methods to enhance engagement with project study populations.**

As discussed, this project struggled to achieve engagement from posters and social media posts advertising surveys and interest forms. We found greater success by actively seeking participants to survey by approaching people in person, and we believe future projects will find similar success. For this project, the survey was short enough to be delivered in person, but for longer surveys, comparable results may be achieved by using a QR code that is advertised by approaching people. An added benefit to in person surveying is deeper insight to respondents' backgrounds and opinions. Engaging in a discussion about the questions rather than simply requesting answers for questions provides qualitative details that may give a better understanding than quantitative values.

7. **Student research projects should remain aware of calendar impacts on the availability of study populations.**

When targeting specific populations, it is important to consider when those populations will be most available. During this study, there were two weeks when students were inaccessible because they were on holiday for Easter. Another example may be when surveying adults during the week, many of your population members will be at work for most of the day. Even when targeting a general population rather than a specific one, these accessibilities should be noted to avoid nonresponse bias from a specific portion of the population. Finding the right times to approach a population is crucial for accruing representative data for a population.

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Appendix A: Sample Interview Questions

These questions are several sample questions that were used in an interview with Tom Collins, Hydrogen Lead at Worcester Bosch. In the interview, these questions were used as a guide, and the order was altered to achieve a natural flow of conversation.

Hydrogen Safety

1. What is your role at Worcester Bosch, specifically in relation to the Hydrogen Boiler project?
2. What piques your interest in hydrogen as opposed to other zero carbon heating options?
3. At what point does hydrogen become “dangerous”?
   a. Concentration, temperature, pressure, etc.
4. What kind of safety standards do you have to adhere to when working with hydrogen in a home setting?
   a. What kind of safety technology do you use to achieve these standards?
   b. Would this technology become a “standard” for safety if hydrogen is adopted across the country?
5. Do you use different technology when working with hydrogen in a lab or work setting (i.e. at Worcester Bosch as opposed to in a demonstration house)
6. How does hydrogen safety compare to natural gas safety?
7. Do you use hydrogen boilers anywhere here in Worcester Bosch other than for testing?

Hydrogen Costs

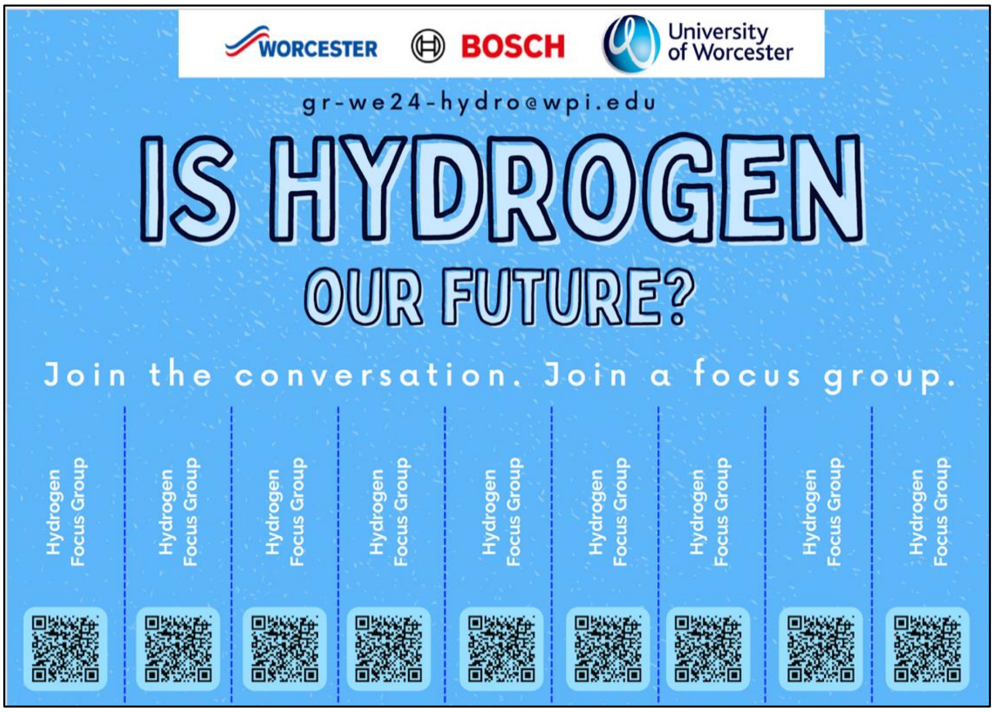
1. How does the efficiency of hydrogen boilers compare to natural gas boilers?
2. Do you have any figures of hydrogen gas costs compared to natural gas?
3. What are the largest infrastructure challenges required to transition the grid to hydrogen?

Hydrogen Perceptions

1. What do you wish people knew more about hydrogen?
2. If you could remove one misconception about hydrogen from people’s minds, what would it be?

Appendix B: Advertising Posters

These posters are some examples distributed to identify respondents for the preliminary screening survey. Posters like these were distributed to local establishments. For some of the posters, an animation was created to be able to catch the eyes of passersby if displayed on television screens. The example posters shown use tabs at the bottom that can be removed so interested people can take the tab with them to take the survey at another time.



Appendix C: Preliminary Screening Survey

This preliminary screening survey served to identify participants for a focus group about hydrogen heating. This survey collected information about the respondent's role at the University of Worcester, or their home ward if they are not affiliated with the University. The results were to be used to identify appropriate participants for focus groups. This survey was distributed through posters and completed through the web service, Qualtrics.

Introduction and Informed Consent

This survey will take about **5 minutes to complete**.

We are a group of students from Worcester Polytechnic Institute in the United States, working with Worcester Bosch, the University of Worcester, and the Heart of Worcestershire College to understand local perceptions of hydrogen for domestic heating. We will be conducting focus groups of people on the University of Worcester campus and in the ward of St Clement to understand their current perceptions of hydrogen for domestic heating. **This survey is designed to identify participants for these focus groups.**

Following the focus group, **participants will be asked to complete a post-focus group survey to assess their opinion after the session**. Those opinions will allow us to assess overall public opinion but improve future focus groups.

Your participation in this survey is completely voluntary. You may withdraw from the survey and the associated research study at any time. All data collected is and will remain anonymous during and after the survey. No names, contact information, addresses, or any other identifying information will appear in questionnaires or in any of the project reports or publications. Worcester Bosch, the University of Worcester, and the Heart of Worcestershire college will use the data collected from this study to understand public perceptions of hydrogen boilers.

A copy of the final study can be provided through an internet link at the conclusion of the study. **Your participation will help shape the future of energy technology.**

Survey Questions

1. Which of the following best describes you?
   a. University of Worcester Student
   b. University of Worcester Staff
   c. Resident of Worcester, UK
   d. None of the above

2. Do you live on the St. Johns campus? (Only visible if question 1 is answered a)
   a. Yes
   b. No

3. Please describe your title at the University of Worcester? (Only visible if question 1 is answered b)
   [User fillable text box]

4. Please select which area of Worcester you reside in. (Only visible if question 1 is answered c)
   a. St. Clement
   b. St. John
   c. Other: [User fillable text box]

5. Are you familiar with the University of Worcester Crime Scene or Ability houses? (Only visible if question 1 is answered a, b, or c)
   a. Yes
   b. No
   c. What are the Crime Scene and Ability houses? (click to learn more about the houses)

> The Crime Scene and Ability houses are two semi-detached houses on the St. Johns campus that are used for specialised teaching.
>
> The Crime Scene house is used by forensic science students to provide hands-on training and examples for evaluating crime scenes.
>
> The Ability house is used by the occupational therapy department to demonstrate what can be achieved to improve accessibility in an ordinary home using innovative and intelligent design.
>
> (Only visible if question 2 is answered b or c)

6. Does your course require you to use the Crime Scene or Ability houses? (Only visible if question 1 is answered a)
   a. Yes
   b. No
   c. I don't know

7. If you are interested in participating in a focus group about hydrogen, please indicate so below. (Only visible if question 1 is answered with a, b, or c)
   a. I am interested.
   b. I am not interested.

8. If you are interested in being notified when the final report is published, please indicate so below.
   a. I am interested.
   b. I am not interested.

9. Please enter your email address. (Only visible if question 7 or 8 is answered as interested)
   [User fillable text box]

Appendix D: Focus Group Guide

The introduction statement and questions below were created as a guide for facilitators to conduct focus group conversations about converting natural gas boilers to hydrogen boilers. Topics include sustainability, carbon emissions, hydrogen knowledge, and comfort using hydrogen in the home.

Introduction to Focus Group Members

The questions for this focus group are intentionally open-ended to encourage discussion about the topics. We seek honest opinions. There are no absurd thoughts or opinions. There are no stupid questions.

Sample Questions

- What are some ways that you practise sustainability in your life?
- What is your understanding of where carbon emissions in the UK come from?
- How familiar are you with home heating systems?
- Are you familiar with any alternate methods of home heating?
- What are your first thoughts when I say "hydrogen"?
- If we told you this room was heated by hydrogen, what would your thoughts be?
    - What if the natural gas was replaced by hydrogen?
- How familiar are you with hydrogen boilers for domestic heating?
- Are hydrogen boilers a viable alternative for domestic heating?
- Would you ever consider using hydrogen-based heating in your home?
- What else would you like to know about hydrogen heating?
- What are your thoughts about a building that you work in or live near being heated by hydrogen?
- What information or resource do you believe would be helpful in increasing public understanding of hydrogen and its applications?
- Do you have any other thoughts or suggestions focused on hydrogen boilers for achieving net zero carbon emissions?

Appendix E: Post Focus Group Survey

The survey below is used to document conclusions participants made by attending a focus group. The results from this survey will assist in facilitating better discussion in later focus groups by spending more time on the topics not adequately covered before.

Introduction and Informed Consent

Thank you for your participation in our focus group! Please fill out this survey to give us your final opinions; it should only take about 10 minutes.

We are a group of students from Worcester Polytechnic Institute in the United States, working with Worcester Bosch, the University of Worcester, and the Heart of Worcestershire College to establish local perceptions of hydrogen for domestic heating. This survey is to understand your reactions and thoughts about the focus group you participated in about hydrogen boilers. Your response will help us assess how your opinions may have changed following the focus group.

Your participation in this survey is completely voluntary and you may withdraw from the survey and the associated research study at any time. All data collected will remain anonymous during and after the survey. No names, contact information, addresses, or any other identifying information will appear in questionnaires or in any of the project reports or publications. Worcester Bosch, the University of Worcester, and the Heart of Worcestershire College will use the data collected from this study to understand public perceptions.

If you are interested, a copy of the final study can be provided through an internet link at the conclusion of the study. **Your participation will help shape the future of energy technology.**

Survey Questions

1. Did this focus group change your opinions/feelings about hydrogen?
   a. Yes, I have a positive opinion.
   b. Yes, I have a negative opinion.
   c. No, I have the same opinion.
2. Have your opinions/feelings changed about use of hydrogen-fuelled boilers? If so, how?
   a. Yes
   b. No

   [User fillable text box]

3. Are there any terms or concepts would you like additional explanation? If so, please include them.
   a. Yes
   b. No

   [User fillable text box]

4. Were there any insights or perspectives from other participants that stood out to you? Please explain.
   a. Yes
   b. No

   [User fillable text box]

5. Were there any questions or other parts of the discussion that were not adequately addressed? Please specify them.
   a. Yes
   b. No

[User fillable text box]

6. Was the information provided during the focus group clear and easy to understand? If not, please elaborate.

[User fillable text box]

7. What topics or areas related to hydrogen do you think future discussions or research should be focused on?

[User fillable text box]

8. Please list any details or information that resonated with you during the discussion.

[User fillable text box]

Appendix F: Wider Public Survey

This survey is used in the wider Worcester area to gain data about public perceptions about hydrogen boilers being used in neighbouring houses. This survey is delivered in person in the form of a structured interview.

Informed Consent

This survey is a part of a research project in collaboration with the University of Worcester, the Heart of Worcestershire College, and Worcester Bosch. This project aims to document public opinions of hydrogen boilers for domestic heating. Your participation is voluntary, and you may withdraw from the survey and the associated research study at any time. No identifiable information will be collected.

Survey Questions

1. How familiar are you with home heating systems?
2. If we told you this room was heated by hydrogen, what would your thoughts be?
3. Would you ever consider using hydrogen-based heating in your home?
4. What information or resources do you believe would be helpful in increasing public understanding of hydrogen and its applications?
5. Would you say you have an overall positive, negative, or neutral opinion on hydrogen for domestic heating?

Appendix G: Hydrogen Sources and Infrastructure

This section is an extended version of the research findings discussed in section 4.1. These topics were researched using WPI resources and databases.

Hydrogen Sources

SMR Hydrogen Production

Steam Methane Reformation (SMR) is a widely employed industrial process for hydrogen production, accounting for approximately 75% of the hydrogen supply in the UK (*Hydrogen Analytical Annex*, 2021). This method involves the reaction of methane (CH_4) with steam (H_2O) in the presence of a catalyst to produce hydrogen gas (H_2) and carbon monoxide (CO). Environmental concerns arise due to the release of CO_2 as a byproduct through SMR. The hydrogen produced by SMR, or other non-renewable means is referred to as "grey hydrogen."

In response to the environmental challenges posed by traditional SMR, there is a growing emphasis on carbon capture technologies to reduce the release of CO_2. Carbon capture and storage (CCS) technologies aim to capture the CO_2 emitted during hydrogen production, store it underground, and prevent it from entering the atmosphere (*Carbon Capture and Storage*, n.d.). Hydrogen produced by SMR utilising CCS is referred to as "blue hydrogen" depicted in figure H1, depicts the process of SMR and CCS. Due to the continued dependence on fossil fuels, SMR and CCS is not desired as a long-term solution.

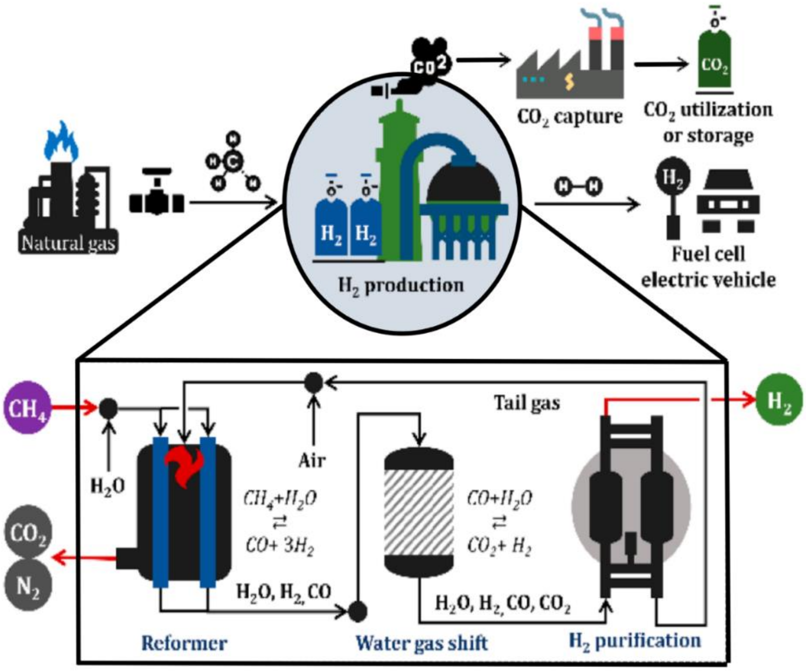


Figure G1: SMR and CCS Process
Adapted from (Lee et al., 2021)

Green Hydrogen

Green hydrogen is produced using electrolysis from renewable energy sources. Illustrated in Figure H2, the green hydrogen production process involves utilising renewable energy sources like wind to power an electrolyser. This device separates oxygen and hydrogen, yielding hydrogen that can be stored and utilised for heating purposes. Green hydrogen has emerged as a sustainable alternative to traditional hydrogen production methods. The efficiency and expense of these methods are considerations in its adoption (*Why We Need Green Hydrogen – State of the Planet*, 2021).

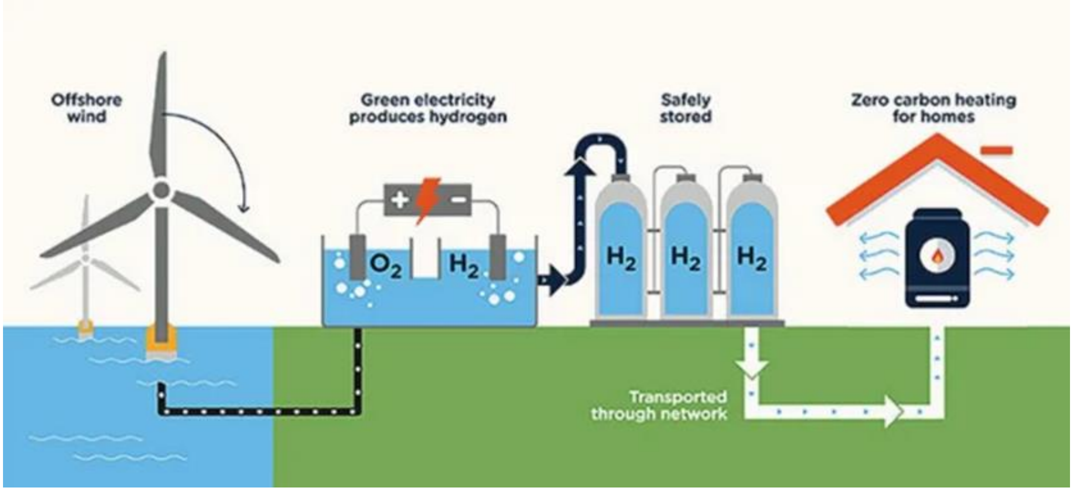


Figure G2: Green Hydrogen Process
(Green Hydrogen Is on the Rise, *n.d.*)

The efficiency of green hydrogen production methods relies on the accessibility and dependability of renewable energy sources. Variations in solar and wind energy can disrupt the uniformity of hydrogen generation. The degradation of materials within electrolysis cells can lead to a drop-off in performance over time (Y. Zhong, personal communication, February 26, 2024). The expense of electrolysis technology and the accompanying infrastructure has posed a constraint on the widespread acceptance of green hydrogen.

Hysata asserts that electrolysis is leading the charge in pioneering advanced technologies aimed at boosting the efficiency and cost-effectiveness of green hydrogen production. Refining the electrolysis process, Hysata seeks to lower the expenses tied to green hydrogen, thus positioning it as a more competitive option in the energy market. (*Our Company – Hysata*, n.d.). Hysata claims to have engineered an electrolyser system boasting an efficiency rate of 95%. The advancements in green hydrogen technology will assist in the reduction of carbon emissions across industries and aiding in the fight against the global climate crisis (*The climate crisis - A race we can win | United Nations, 2020*).

Hydrogen Infrastructure

Companies including Baxi Heating and Vaillant, have made steps towards developing their own "hydrogen-ready" boilers. These companies, along with Worcester Bosch, are participating in their own trial runs and demonstration projects using these hydrogen boilers to test capabilities, as well as learn more about some of the challenges that come with running hydrogen boilers.

Pipelines

One characteristic of hydrogen that makes its transportation challenging is a phenomenon – known as hydrogen embrittlement, in which metals such as Cr-Mo steel SCM435 (typical for storing hydrogen), can degrade due to the presence of hydrogen. Crack growth rates in containers storing hydrogen were 30 times higher than those that did not contain hydrogen (Murakami, 2019).

The UK hydrogen pipeline network begins at the distributor with larger, higher-pressure (70-94 bar) transmission lines, often made of high-strength steel. To transition to a hydrogen-based heating network, pipes would need to be made of softer steel or polyethylene to minimise the effects of hydrogen embrittlement, requiring the replacement of many high-pressure pipelines across the country (Dodds & Demoullin, 2013). The UK government started an iron mains replacement program (IMRP) in 1977 aimed to be completed in 2032 with the goal of replacing all gas lines within 30 meters of buildings with polyethylene pipes (Dodds & McDowall, 2013). To accommodate hydrogen, this program may be able to be modified to replace all other iron lines with polyethylene, although this would be unlikely to be completed by the 2030s (Dodds & Demoullin, 2013).

Storage

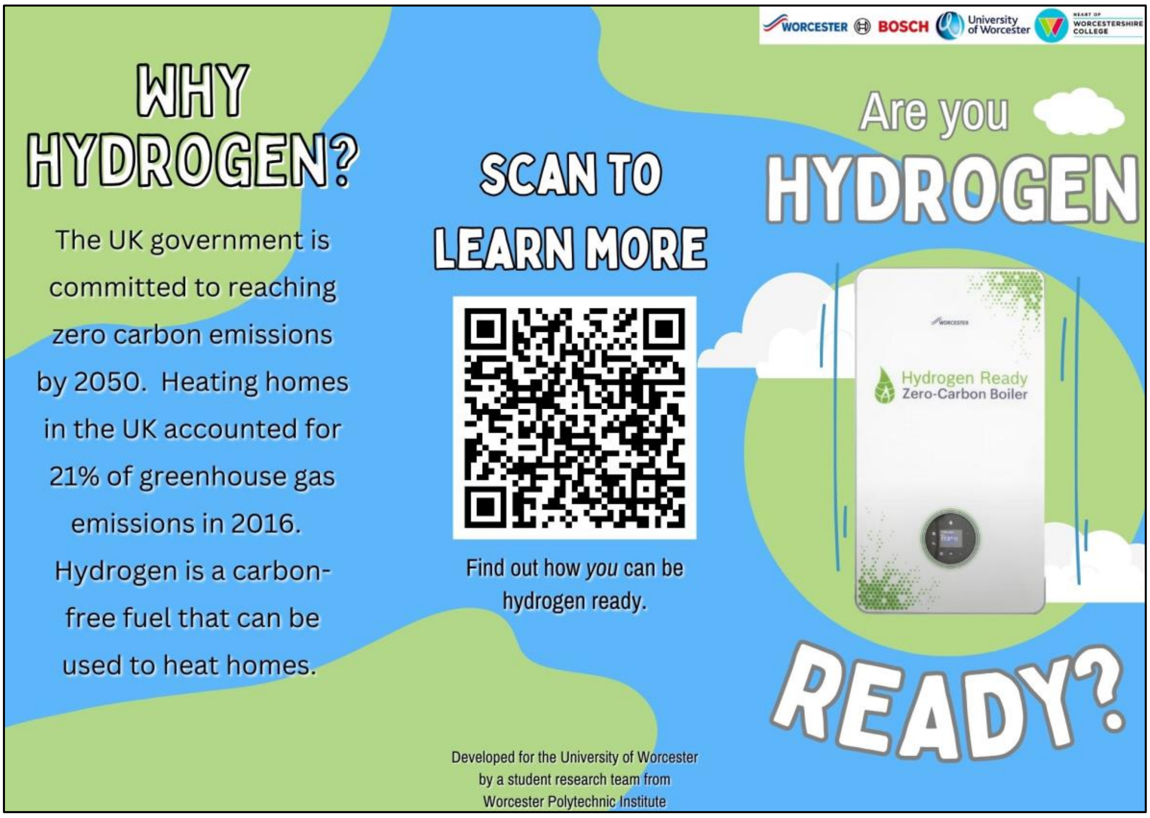
Hydrogen has low energy concentration by volume due to its lower molecular weight and ability to be compressed to high pressures. This complicates its storage as an energy source, as at atmospheric pressure, a higher volume of hydrogen would be needed to provide the same amount of energy as natural gas. Some solutions involve pressurising the gas to extremely high pressures to maximise the energy per unit volume. This approach, however, increases the effect of hydrogen embrittlement due to the higher pressure (Laureys et al., 2022). The effects of this method of storage have proven problematic and costly.

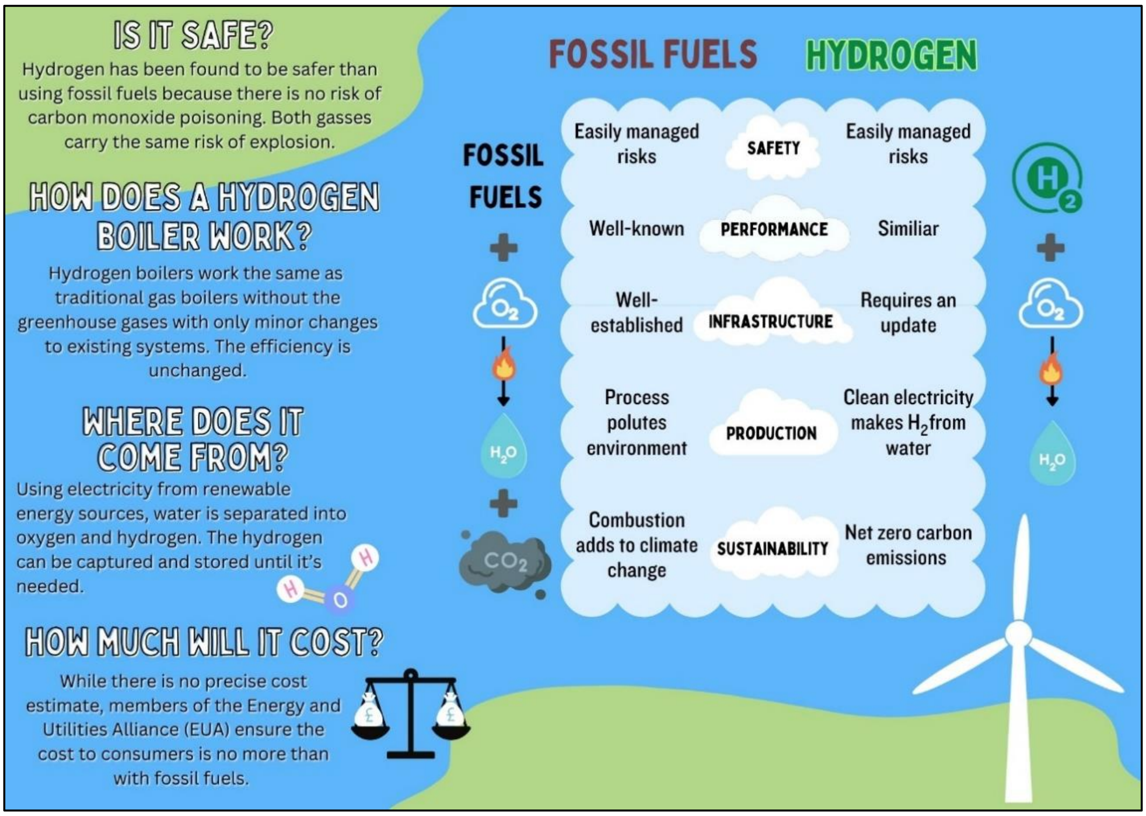
An alternative to storing gaseous hydrogen at high pressures would be to store liquid hydrogen in tanks designed with higher thermal insulation designed specifically for liquid hydrogen. Currently, liquefaction costs for hydrogen are decreasing as more effort and research are being put into it. Liquid hydrogen also provides higher volumetric storage density than gaseous hydrogen compressed to 70MPa (Yin et al., 2024). If the price of liquefaction does not outweigh the price of consistent maintenance and monitoring required for gaseous hydrogen storage, liquefaction can become a powerful, energy-dense storage solution for hydrogen.

One storage method being considered is one that has been used for decades: underground storage. Many gas companies already use underground geological formations to store natural gases, and some companies are using them to store carbon dioxide captured from the atmosphere to reduce carbon output. One study aimed at proving the viability of this concept calculated that offshore gas fields could easily accommodate the seasonal variations in demand for hydrogen. This study further argued that the hydrogen would take up so little space that it wouldn't even need to compete with other underground applications, such as carbon recapture and storage (Mouli-Castillo et al., 2021). This method of storage would likely prove to be much more cost-effective than above-ground tanks because the infrastructure for underground storage already exists and would just need to be adapted for hydrogen use.

Appendix H: Educational Material, Brochure

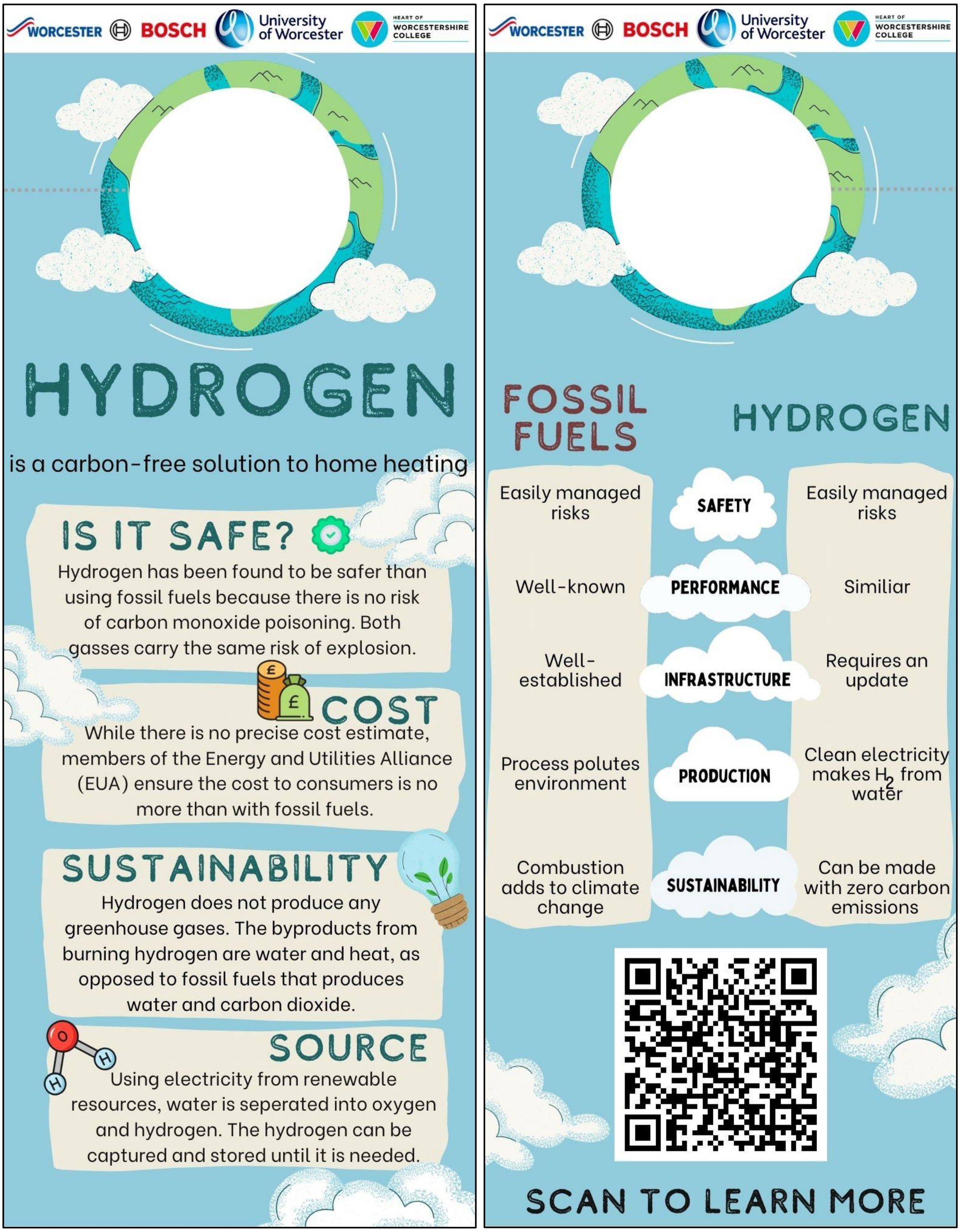
The brochure was developed as a general guide for the five most discussed topics of interest.





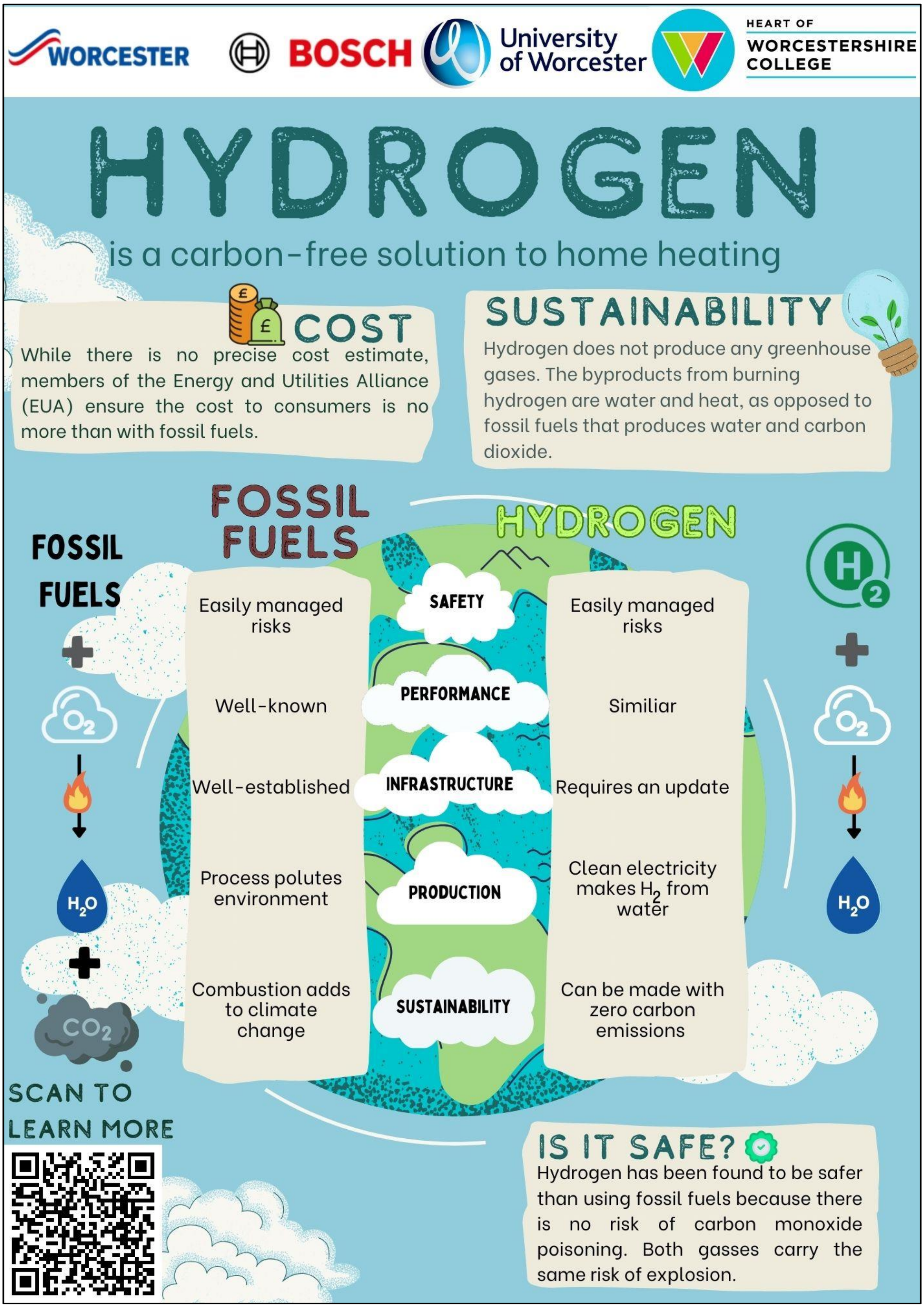
Appendix I: Educational Material, Door Hanger

The door hanger was developed for the UK residents. Topics covered were created based on the interests obtained from surveying the general population. The door hanger focuses on what the UK residents were interested in learning more about.



Appendix J: Educational Material, Poster

The poster was created based on student survey responses. Specifically addressing their concerns and knowledge gaps. The poster can be posted around campus in highly trafficked areas to raise awareness to the student population.



Appendix K: Interview Informed Consent

This form is used to seek informed consent from interview participants in both technical interviews and in opinion-based interviews. It provides a general background of the project and how their participation in the survey will benefit the research. The form also provides information about confidentiality and voluntary participation. A paper copy may be signed, however, if the participant verbally agrees and a witness is present, the researchers may document that agreement.

Title of Research Project: Understanding Community Perceptions of Hydrogen as a Domestic Heating Fuel

Researchers: Eric Aimone, Cece Daniele, Donovan Joyce, Sean Obert

Introduction:

We request your participation in an interview as part of a research project.

The purpose of this study is to document and evaluate public understanding and perceptions of hydrogen as a domestic heating fuel. We plan to document some of the technical processes and infrastructure requirements of hydrogen, as well as the costs and considerations of implementing hydrogen into the heating network.

Procedure:

The interview will consist of several open-ended questions and could last up to an hour. The questions concern the technical process of hydrogen production, its infrastructure, and its costs.

Confidentiality:

Your identity will be kept confidential unless we decide to quote you, in which case we will seek your permission prior to publication. Any information shared during the interview will only be used for the purpose of this research project. None of the information collected will be attributable to any individual and all data collected will be stored on password protected devices.

Voluntary Participation:

Your participation in this interview is completely voluntary. You have the right to refuse to answer any question or withdraw from the interview at any time without consequence.

Contact Information:

If you have any questions or concerns about the research project or your participation in the interview following this interview, please feel free to contact us at gr-we24-hydro@wpi.edu.

Consent:

By participating in this interview, you acknowledge that you have read and understood the information provided in this consent form. You agree to voluntarily participate in the interview and understand that you can withdraw at any time without consequence. Your consent will be recorded at the beginning of the interview.

Participant's Signature: _____________________ Date: _______________

Researcher's Signature: _____________________ Date: _______________

[If the participant agrees to participate verbally, the interviewer can sign and date on behalf of the participant.]