Hy4Heat
demonstrating
hydrogen for heat

Department for
Business, Energy
& Industrial Strategy

WORK PACKAGE 5

Understanding Commercial Appliances

Hy4Heat WP5: Understanding Commercial Appliances for UK Hydrogen for Heat Demonstration

Final Report

26 October 2020

Project No.: 0480403

for

Department for Business, Energy & Industrial Strategy

The business of sustainability

ERM

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26 October 2020

Hy4Heat WP5: Understanding Commercial Appliances for UK Hydrogen for Heat Demonstration

Final Report

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1. EXECUTIVE SUMMARY

1.1 Mission Statement

The 'Hydrogen for Heat' (Hy4Heat) programme aims to support the UK Government in its ambitions to decarbonise the UK energy sector in line with the targets of the Climate Change Act 2008, by attempting to evaluate and de-risk the natural gas to hydrogen network conversion option.

The impact on the commercial sector is an important factor in understanding the feasibility of utilising hydrogen to decarbonise heat in the UK. The overall objective of the market research study Work Package 5 (WP5) was to determine if it is theoretically possible to successfully convert the commercial sector to hydrogen. This work will contribute to the understanding of the scale, type and capacity of gas heating appliances within the sector, providing a characterisation of the market and determining the requirements and feasibility for successfully transitioning them to hydrogen in the future.

1.2 Definition of Commercial

Hy4Heat WP5 was focused on appliances and equipment providing heating needs in the commercial sector which are currently fuelled by natural gas through the below 7 bar gas network. For the purposes of this study, ‘commercial’ considers all gas fired appliances installed in ‘non-domestic’ premises used for space heating, sanitary water heating and catering purposes up to an output rating of 1 MW. Non-domestic premises are largely represented by those involved with commerce, public administration, agriculture and industry.

Two key distinctions are made in defining a commercial appliance. Firstly, the output rating of the appliance, where a lower and upper threshold is identified to separate commercial use from domestic and industrial use respectively. The lower threshold typically distinguishes between the differing design requirements for appliances intended for use in domestic versus commercial settings. Secondly, the appliance end use setting, as indicated by natural gas consumption statistics for the commercial sector, is taken into consideration.

The study acknowledges that there is some overlap in the considerations of appliance rating and end use setting when determining where the appliance is ‘commercial’; there are scenarios where a ‘commercial’ appliance is installed in a ‘domestic’ setting, and vice versa where a ‘domestic’ appliance is installed in a ‘commercial’ setting. To address this, the study employed both top down and bottom up approaches to estimate the installed appliance numbers, combining natural gas consumption data with appliance sales data where available.

1.3 Main Findings

Market Characterisation

The market study conducted for WP5 was arguably the largest and most in depth consideration of natural gas appliances in the UK commercial sector to date. Engagement with key stakeholders revealed that sector level population data does not exist for most appliances, and that the commercial sector is heavily segmented, reflecting the diversity of the commercial appliance market.

The installed market for commercial natural gas fired heating appliances is estimated to be 1.5 million units (likely range 1.0 – 2.0 million units) within the 2.0 million non-domestic premises in the UK. The wide range of the estimate reflects the level of uncertainty in the input data used for this study, which was derived from a combination of sources.

Natural gas consumption for heating in the commercial and industrial sectors totalled 103.6 TWh in 2017, with the major uses being space heating (78%), hot water (9%) and catering (6%). In line with the consumption data, space heating appliances are the largest contributor to the overall installed base.

Boilers are the most populous appliance in the commercial sector, with an estimated installed base of approximately 500,000 commercial sized units (30 kW – 1 MW). Dry space heating appliances are the next most populous, with an estimated 300,000 warm air heaters and 300,000 radiant heaters currently installed.

It is estimated that there are 200,000 gas fired commercial water heaters in the UK providing sanitary hot water.

Confidence in the estimates for installed base of boilers and water heaters is high, as a result of the aggregated sales data maintained by the relevant trade body. Confidence in the estimates for warm air and radiant heaters is lower, since aggregated sales data is not kept for these appliance types.

There are an estimated 250,000 gas fired commercial catering appliances installed in commercial kitchens in the UK. Ranges are the most common, due largely to their versatility, followed by fryers and salamander grills. However, as there is no industry aggregated sales data for commercial catering appliances, confidence in the population estimate is low.

An estimated 66,000 gas fired tumble dryers are installed in numerous commercial settings, including universities, prisons, laundrettes and hospitals.

The relative distributions of gas fired commercial appliances within the commercial subsectors and end use settings is not well known. The exception to this is boilers in the public sector, due to the significant amount of data obtained from of a large Freedom of Information (FOI) campaign carried out as part of the market study.

It is estimated that up to 80% of all commercial boilers are less than 150 kW rated input. Up to this size it is expected that technology for domestic sized hydrogen boilers could be used to meet light to medium commercial heating demands, either using a cascade of domestic sized boilers (< 30 kW) or a scaled-up commercial variant (30-70 kW). However, it is acknowledged that the challenges involved in designing boilers to meet safety, emissions and efficiency targets become greater as the appliance output rating increases.

Heavy-duty commercial boilers over 400kW in rated input, which are generally non-condensing with pressure jet type burners and outside the scope of the Ecodesign Directive, are estimated to account for approximately 3% (15,000) of the installed base of commercial boilers.

Technical Challenges and Appliance Development

The technical challenges to developing hydrogen appliances for use in the commercial sector are deemed to be surmountable and should largely be addressed by domestic appliance development programs already underway and existing hydrogen boiler applications in the industrial sector. The proof of concept with domestic appliances that successfully demonstrate stable hydrogen combustion, reliable flame detection and safety systems, and achieve efficiency and emissions targets with suitable materials of construction proven to maintain gas tightness, should support the view that it is technically feasible to develop commercial appliances which run on 100% hydrogen, as many of the components are shared (or are scaled up versions) and sourced from a relatively small pool of manufacturers/suppliers.

The key differences in the technical challenges faced by manufacturers in the development of appliances for the commercial sector, compared to the domestic and industrial sectors, are:

- increased effort, in terms of design and technical complexity, to achieve functional safety of the appliance (i.e. consequences of delayed ignition explosions could be much greater than domestic);
- larger variety of burners must be developed to safely and efficiently deliver the wide range of heat inputs required by commercial appliances (i.e. 5 kW commercial hob burner through to 1 MW pressure jet burner for shell boiler);

- more complex design and optimisation for appliance heat transfer, efficiency and emissions (e.g. non-linear increase in combustion chamber volumes when scaling up from domestic; desire to achieve same footprint as current natural gas appliances when scaling down from industrial appliances with additional low NO_x technology/abatement);
- ‘bake quality’ and cooking time are more critical as meals are the commercial product and livelihood of most catering end users;
- cascading of multiple smaller units to meet large peak heating demands with high turn-down ratios; and
- appliance installation considerations such as hazardous area rating, certified equipment specification, fresh air supply, flue arrangements, plant room gas detection and associated safety shutdown.

It is acknowledged that many of these items are not ‘barriers’, rather they are areas where significant effort and investment is likely to be required in the research and development phases.

The development of ‘hydrogen ready’ appliances, which are designed to work optimally on 100% hydrogen following some minor amendments, but can also function safely on natural gas prior to this, has been identified by manufacturers as the key for successful transition to using 100% hydrogen for heat.

Wider Challenges

The diversity of commercial buildings (see Section 4.1.2 for detailed definition) is much greater than for the domestic sector in terms of their physical size and heat demand. This diversity, coupled with the low fuel consumption relative to the domestic and transportation sectors (in terms of overall consumption) and industrial sector (in terms of energy intensity), has meant that while decarbonisation continues to grow in profile, the commercial sector has received much less attention than other sectors to date.

No significant development of commercial appliances has been identified to date, and this reflects both the relatively small market for commercial appliances in the UK, both in comparison to the domestic appliance market in the UK and more broadly to the worldwide commercial appliance market (i.e. no ‘pull’) and a perceived absence of a clear policy or vision for a hydrogen economy in the near future (i.e. no ‘push’).

While it is deemed technically feasible to develop commercial appliances to function safely and effectively with 100% hydrogen, the challenge to do so cost effectively is considered to be far greater.

Securing User Acceptability

Knowledge of hydrogen and its potential to replace natural gas as a fuel for heating is generally low within the commercial end user population. Currently there is a perception among some end users that hydrogen may be unsafe for commercial use. However, there is also an acceptance from some end users that the safety case for hydrogen would need to be approved before the decision supporting mass conversion is made.

Costs and Timelines for Sector Conversion

The cost to convert commercial sector appliances from natural gas to 100% hydrogen based on manufacturer feedback received during the 2019 engagement campaign is estimated to be £10.1 - £14.3 billion. This estimate is based on a Monte Carlo analysis of the ‘per unit’ conversion/replacement cost multiplied by the installed base for the appliances studied. No account is made for significant changes to overall energy demand and technology prevalence between now and the start of conversion.

As stated above, this base case estimate reflects the feedback from appliance manufacturers at the time the analysis was undertaken (August 2019). However, this is a rapidly developing field and recent comments by manufacturers suggest the cost of hydrogen ready appliances might reduce further relative to a gas boiler. To reflect this, a sensitivity analysis was undertaken to investigate the potential impact on conversion costs if hydrogen ready appliances are less expensive than the view indicated by manufacturers during the study. This sensitivity resulted in a cost to convert commercial sector appliances of between £8.9 and £11.2 billion.

Wall hung and floor standing pre-mix boilers (boilers which utilise burners that blend air and natural gas to within flammable limits prior to the point of ignition), with rated outputs of 400 kW or less, are predicted to contribute the most to the overall conversion cost, both in magnitude (due to the relatively large installed base) and uncertainty (due to the current lack of understanding of what proportion of boilers could be converted rather than requiring replacement with a new hydrogen appliance). The base-case model assumes 50% of boilers are replaced and 50% are hydrogen ready appliances which are converted. Currently installed stock (non-hydrogen-ready) is not considered technically or economically feasible to convert.

The Monte Carlo analysis was performed on key input variables to determine the sensitivity of the cost estimate to uncertainty in the inputs. The main contributors to uncertainty in the overall cost estimate are:

- The cost of a new 100% hydrogen appliance (relative to current natural gas appliance).
- The percentage of pre-mix boilers which can be converted rather than require replacement with a new 100% hydrogen appliance. The base-case model assumes non-hydrogen-ready appliances cannot be converted, so must be replaced.
- Ancillary costs incurred during the conversion process (e.g. pipework replacement).

Figure 1-1 – Total to Convert or Replace All UK Appliances (Inputs ranked by effect on output mean)

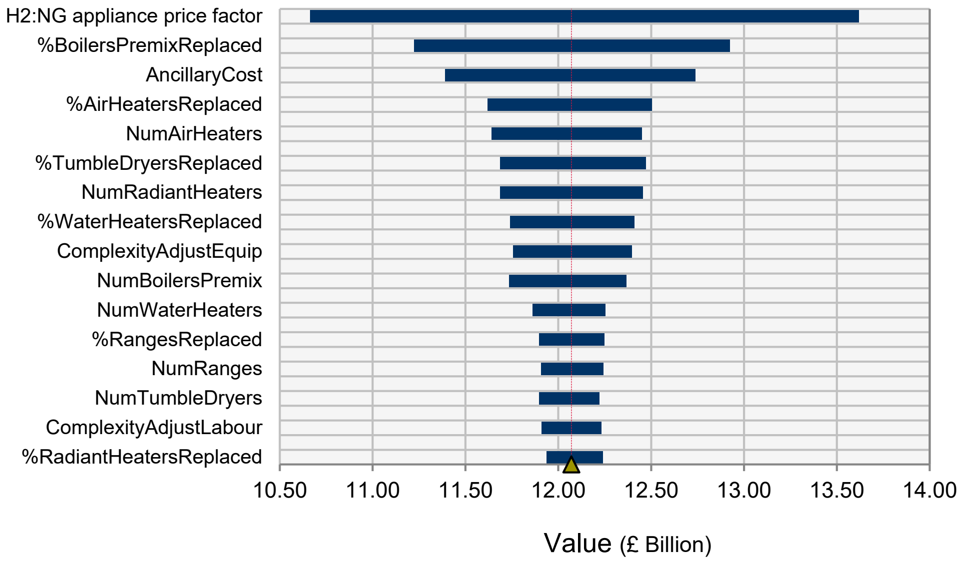
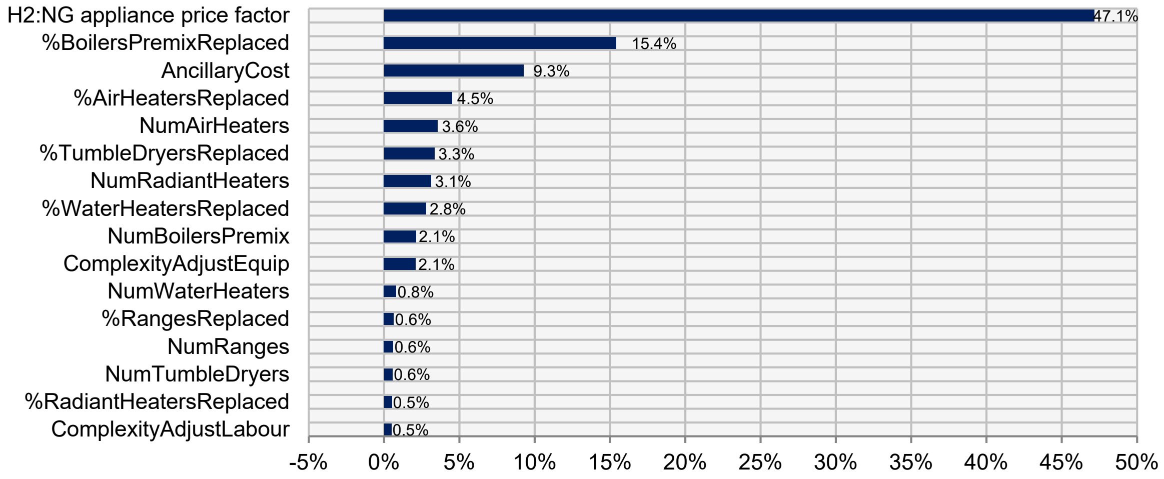


Figure 1-2 – Total to Convert or Replace All UK Appliances (Contribution to variance)



1.4 Main Recommendations for Hy4Heat and Government

As a result of the market research conducted for Work Package 5, a set of recommendations has been proposed to help the Hy4Heat team and BEIS prepare for potential community trials with hydrogen fuelled commercial appliances. The recommendations are grouped into three key themes.

1. Improved Data Quality

1.1. Many of the assumptions used in the cost model are based on a small set of data points. This was due largely to limited engagement responses for many of the key stakeholders in the commercial sector, many of whom identified the lack of a business case for investing in hydrogen development for not participating further. A further tranche of stakeholders would not engage with the WP5 team – it is considered that this decision related to a lack in business relevance of hydrogen transition to the majority of those unwilling to engage in dialogue. It is recommended that commercial sector stakeholders are mapped according to their influence and interest in hydrogen transition, and to develop a proactive strategy to increase the level of interest for key stakeholders such as trade bodies, facilities management companies, national retailers, etc.

1.2. The cost model includes some significant assumptions to account for the uncertainty in the input data. It is recommended that BEIS and the Hy4Heat team review the assumptions with manufacturers taking part in WP5b to refine the overall cost estimate, focussing on those assumptions which make the greatest contribution to actual cost and uncertainty in the cost estimate.

1.3. Through engagement with the relevant trade association, FEA, and its members, this study found that there are no industry aggregated statistics for commercial catering appliances installed in the UK. The level of confidence in commercial catering appliance counts presented in this report and their distribution across the subsectors is therefore low. It was found that detailed knowledge of the make-up of the commercial catering market in terms of food service outlets and the appliances installed within those kitchens is collectively held by a small number of private consultancies and industry experts. It is recommended to engage with FEA to commission a detailed study of the commercial catering sector to improve the estimate of installed gas appliances in the UK.

1.4. The level of engagement with private sector stakeholders was generally low, and as such private sector appliance populations and their distributions across the subsectors and end use settings is largely unknown, most notably for warm air and radiant heaters. It is recommended that BEIS and the Hy4Heat team engage further with relevant private sector stakeholders, such as large end users and facilities management companies, to provide them with more detailed information relating to developments in the hydrogen economy and potential policy mechanisms, in order to improve the value proposition for them providing data on installed appliances.

2. Appliance development

2.1. Engagement with commercial appliance and component manufacturers and others within the appliance development and supply chain was often limited to general discussions due to the potential for intellectual property rights infringements. Step changes in industry, such as the potential conversion of the national gas grid from natural gas to hydrogen, are often more successful when the industry comes together to work towards a common goal. It is recommended that BEIS and Hy4Heat work closely with the relevant trade bodies to promote knowledge sharing within and between appliance and component manufacturers to ensure that economies of scale are maximised for early development of hydrogen appliances which can be cost competitive.

3. Hydrogen awareness

3.1. Commercial end users are generally unaware of the potential for hydrogen to replace natural gas as a fuel for heating, and are already replacing existing fossil fuel heating appliances with other renewable/low carbon options. It is recommended that a campaign of public engagement is commissioned, to educate commercial end users and those responsible for commercial space heating selection on hydrogen safety, the potential benefits of using hydrogen as a fuel for heating, and current developments in the establishment of a hydrogen economy.

4. Community Trial

4.1. The following commercial appliances are recommended for inclusion in any potential community trial. The appliances have been selected based on a set of criteria including installed base, contribution to annual gas consumption, being unique to the commercial sector.

- Boiler (<70 kW) installed in cascade arrangement of two or more units
- Warm air heater
- Radiant tube and/or radiant plaque heater
- Commercial catering appliances
    - Range
    - Fryer
    - Grill
    - Chargrill
    - Combination Oven

4.2. The choice of site for a small community trial should consider the variety of premises which are present in the UK commercial sector. If a single site is to be selected, the site should have the following buildings to prove the key heating requirements of the commercial sector:

- Large indoor space where wet central heating is required (e.g. offices)
- Large indoor space where radiant heating is required (e.g. gymnasium)

- Large indoor space where warm air heating is required (e.g. workshop)
- On-site kitchen providing large number of meals per day

Using the above criteria, a single site which is likely to fulfil all of the requirements includes a school, university, prison, hospital and fire station. Alternatively, a small village or commercial centre could be selected, thereby allowing for more end use settings to be included. A study should be commissioned, or nomination process commenced, to identify the most suitable location which covers the most representative spread of commercial premises.

2. INTRODUCTION

2.1 Background

Heating is essential to our lives – it is the biggest reason we consume energy in our society and is responsible for over a third of the UK's carbon emissions. Meeting the UK Government's 2050 net-zero target means that heat in buildings will need to be almost completely decarbonised.

There is no clear consensus on the best approach to decarbonising heat at scale. However, there are a number of options with potential to play an important role. One of these is to utilise low carbon gases such as hydrogen. Over 80% of homes and business are currently supplied by gas and the UK has one of the most comprehensive gas networks in the world with 282,000 km of gas pipes feeding 22.7 million buildings.

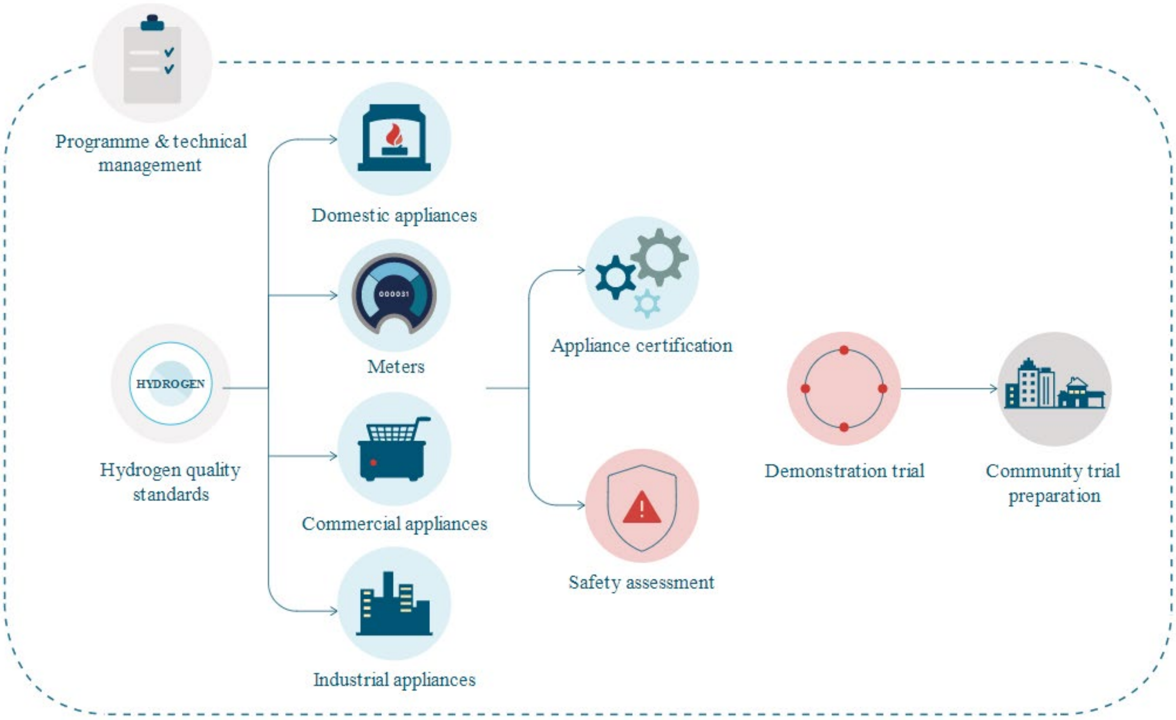
The Department for Business, Energy and Industrial Strategy (BEIS) has appointed Arup+, a group of companies led by Arup, as the Programme Management Contractor (PMC) to manage and successfully deliver Hy4Heat, a programme to demonstrate and begin to prove the safety case for the use of hydrogen for heating in UK homes and businesses.

The Hy4Heat programme's aim is to establish if it is technically possible and safe to replace methane with hydrogen in commercial and residential buildings and gas appliances. This will enable the Government to determine whether to proceed to a community trial.

The programme's focus is on researching, developing, testing and demonstrating within the end-use stage of the gas supply chain. This will involve the gas appliance and equipment sectors as well as consumer research.

The Hy4Heat programme is split into several work packages covering the range of end use application, safety, in-use emissions, and functionality within the sphere of hydrogen conversion; the Hy4Heat work packages are illustrated in Figure 2-1.

Figure 2-1 – Hy4Heat Work Packages



Source: https://www.hy4heat.info/wp1

ERM (Environmental Resources Management Limited) was awarded the contract to deliver work package five (WP5), commercial appliances, in the second half of 2018. This report is the principal deliverable of WP5.

2.2 Project Objectives

The Hy4Heat programme's overall objective is:

- To provide the technical, performance, usability and safety evidence to de-risk the use of hydrogen for heat in buildings whilst working with others to prepare for a potential future occupied trial.

To help Hy4Heat meet its overall project objectives, through better understanding of the Commercial sector, WP5 has the following learning objectives:

- Market Characterisation – provide data on the installed base of commercial heating appliances.
- Technical Challenges and Appliance Development – identify and describe the technical challenges to developing equivalent appliances for use with hydrogen 100% hydrogen.
- Securing User Acceptability – identify the key concerns for end users and measures to overcome.
- Costs and Timelines for Sector Conversion – estimate the overall cost to convert the Commercial sector, with analysis of the key contributors
- Emissions and Efficiency Standards for Heating Appliances – discuss the potential implications of conversion to hydrogen on current and future limits for emissions and efficiency.
- Wider Barriers and Facilitators – other factors that may help or hinder the development of hydrogen appliances for use in Commercial heating applications.

2.3 Scope

The scope of the WP5 study covers the following applications:

- Commercial catering, from tiny café to largest commercial kitchen, but excluding industrial food preparation.
- Heating sub-divided into:
    - Hot water (< 1 MW)
    - Warm air heaters
    - Radiant heaters.

The investigation includes all appliances and equipment providing the heating needs identified above which are currently fuelled by natural gas through the below seven bar gas network and their replacements with hydrogen fuelled equivalents. Commercial scale Combined Heat and Power (CHP) sites and steam boilers are excluded from the scope of this study.

WP5 covers the Commercial sector and, for the purposes of this study, encompasses the commerce and public administration subsectors within the service sector, plus space heating, hot water and catering within the industrial sector.

The commercial framework or policy mechanism required to facilitate conversion of the Commercial sector to hydrogen is viewed as important by BEIS in a wider context, but is outside the scope of this study.

2.4 Report Layout

This purpose of this report is to communicate clearly to the reader work completed as part of WP5, the insights relevant to Hy4Heat, the implications for conversion of the commercial sector to 100% hydrogen and to set out clear recommendations to enable Hy4Heat and BEIS to progress to unoccupied trials with appliances developed to run on hydrogen. The structure of the report is illustrated in Figure 2-2.

Figure 2-2 – Overview of WP5 Report Structure

Introduction	• Provides project background • Details of Hy4Heat and WP5 objectives • Summarises report philosophy and structure
Study Approach	• Outlines the market research study activities • Describes the Stakeholder Engagement Plan
Understanding the Commercial Sector	• Defines the Commercial sector in terms of gas consumption, end use and appliances • Provides estimates of installed base for gas appliances, including breakdowns by type, sector, age, etc.
Technical Challenges	• Describes appliance level technical challenges related to operating with 100% hydrogen in place of natural gas • Discusses implications for appliance development
Wider Challenges	• Highlights the market / economic challenges for commercial appliance development • Discusses the challenges for securing user acceptability
Costs & Timelines	• Describes model of development and conversion costs • Discusses potential costs for conversion of the Commercial sector and the main cost drivers
Conclusions	• Summarises the main findings from the market research • Outlines the current knowledge gaps which are required to be filled
Recommendations	• Presents a set of recommendations for Hy4Heat and BEIS to successfully demonstrate the feasiblitity of converting the Commercial sector to 100% hydrogen for heating

Text presented in boxes (as shown on the right) represents identified gaps in knowledge; these boxes are located in the report sections that provide the most suitable context for the gaps being identified.

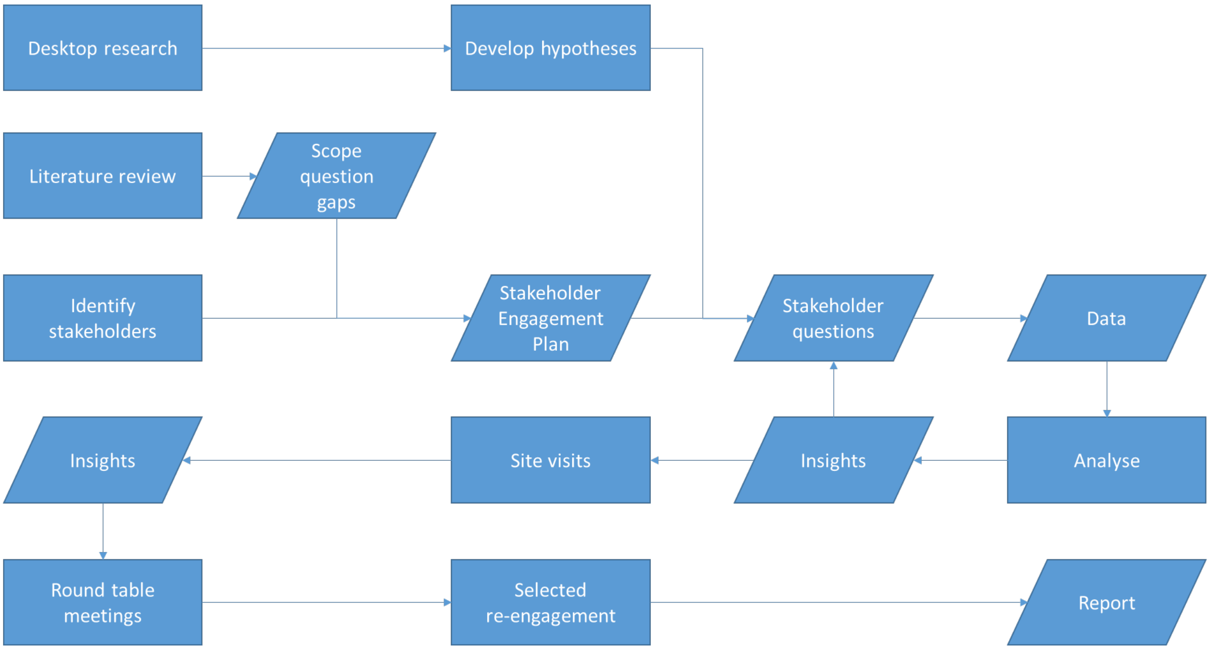
Identified knowledge gaps are shown in boxes like this.

3. STUDY APPROACH

This report is a ‘market study only’ to determine whether it is technically feasible to transition the Commercial sector from natural gas to 100% hydrogen.

Figure 3-1 shows the main tasks that make up the initial study approach for WP5.

Figure 3-1 – Overview of WP5 Work Plan



Source: ERM Project Plan

It is useful to consider the work plan simplified into core tasks:

- Desktop research;
- Stakeholder engagement;
- Data analysis; and,
- Reporting.

Desktop research, stakeholder engagement and data analysis are discussed in the following sections.

3.1 Desktop Research

Desktop research is the foundation of the study; it enables the study team to determine what information is already available on the WP5 study topics and helps to frame what information needs to be sought from stakeholders.

The desktop research for WP5 comprises extensive work via the Internet to examine the current sales market for commercial gas appliances and low-carbon alternatives. In parallel, a comprehensive literature review based on published reports, research papers, text books was conducted.

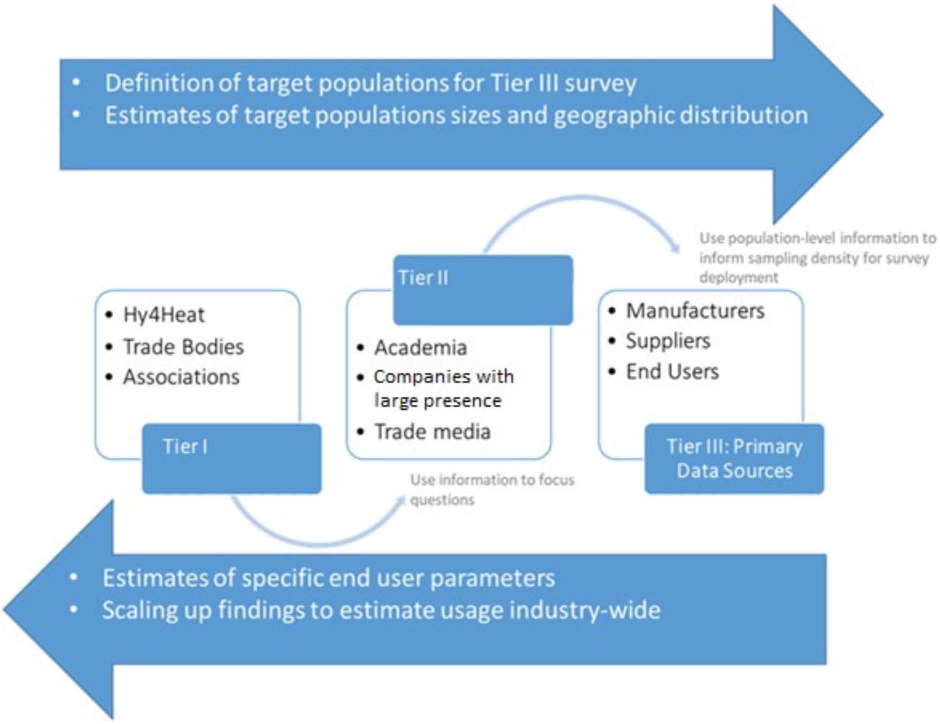
This review of literature for commercial gas appliances highlighted the scarcity of relevant data on the scale, type and capacity of appliances in the commercial sector, and it is discernible that development of hydrogen compatible commercial appliances is lagging behind the Domestic and Industrial sectors. This reinforced the importance of the stakeholder engagement activities, and the reliance on information and data provided by key stakeholders in the Commercial sector.

3.2 Stakeholder Engagement

3.2.1 *Multi-Tiered Engagement Plan*

Given the scale of the Commercial sector, the project Stakeholder Engagement Plan (SEP) is based on a tiered approach, as illustrated in Figure 3-2.

Figure 3-2 – Multi-tiered Stakeholder Engagement Plan



Source: ERM Stakeholder Engagement Plan

The tiered approach described in the project SEP seeks to build on relationships with key stakeholders as gatekeepers and influencers in the commercial gas appliance sector, i.e. engagement with gatekeeper stakeholders should yield access to a wider set of prioritised stakeholders in the next tier. An underlying premise of the SEP is that navigation through stakeholders is an iterative process where targeted stakeholders, engagement methods, etc. may need to be adjusted based on feedback (or lack thereof) from the initially targeted stakeholders.

Within the SEP tiers, a prioritisation of ‘high’, ‘medium’ or ‘low’ applies to each identified stakeholder in order to engage with them strategically and in the most effective manner.

- ‘High’ priority applies to stakeholders with potential access to a large, relevant population; and/or ability to generate unique significant insights; and/ or low level of engagement effort needed to access a Hy4Heat interested population – most effort is targeted at the high priority stakeholders
- ‘Low’ priority applies to a small relevant population with respect to engagement effort and/or low relevance of Hy4Heat to population – these stakeholders are identified for completeness, but the likelihood of project resources making contact is low.
- ‘Medium’ priority applies to stakeholders that do not fit into the ‘High’ or ‘Low’ definitions, and these were to be considered on a case-by-case basis for engagement.

3.2.2 Methods for Engagement

In order to maximise the quality of the information obtained as part of the stakeholder engagement process, a variety of engagement methods were planned. The majority of engagement was planned around interviews (one-to-one meetings or phone calls) and surveys.

To supplement the information gathering process, Freedom of Information (FOI) requests were issued to relevant public sector organisations to gain insights into the types, numbers and capacities of gas appliances that are currently in use.

The respective trade associations for heating and hot water and catering appliances, ICOM and FEA, were the focal point for engagement with appliance manufacturers, and were significant contributors to the study themselves. ERM were invited to attend various technical meetings with ICOM and FEA where group discussions with the appliance manufacturers were held.

Following a period of engagement, members of the WP5 team from ERM and Health & Safety Executive (HSE) Science Division conducted site visits to representative appliance manufacturers and round table sessions with key stakeholder groups. The objectives of these exercises were to ask specific technical questions to enrich insights, whilst group discussions were to be used to validate the outcomes of the data analysis and potentially offer the opportunity to gather new data and inform targeted re-engagement on specific issues where necessary.

3.2.3 Project Engagement Experiences

Stakeholder engagement was carried out with varying levels of success and effort required for effective engagement with the three tiers. A summary of the key successes and challenges for each tier of engagement is provide in Table 3-1 and discussed further below.

Table 3-1 – Stakeholder Engagement Successes and Challenges

Tier	Successes	Challenges
1	Hy4Heat WP5 team – guidance on technical and market challenges and suggested stakeholders for engagement ICOM – constant dialogue with WP5 and ICOM members; multiple invitations to technical meetings; provided sales data (where available); guidance on technical and market challenges and suggested stakeholders for engagement FEA – constant dialogue with WP5 and relevant membership; multiple invitations to attend technical meetings; acted as voice of the members	Other Hy4Heat WPs – lack of knowledge sharing due to IP and confidentiality agreements FEA/CEDA – no central data for appliance sales/installed base

Tier	Successes	Challenges
2	National Facilities Management (FM) company – active interest in potential hydrogen economy Public sector organisations – response rates and quantity of data on installed gas appliances obtained via Freedom of Information (FOI) requests	National Facilities Management (FM) company – data sharing restrictions limited insights into private sector end users Public sector organisations – format and quality of data obtained via FOI requests Academia – largely focused on their own research fields which did not include relevant commercial appliance development; considerable focus on fuel cells and CHP
3	Manufacturers – very open to one-to-one discussions (although typically 'in confidence'); active participation in WP5 and trade body events Large national and multinational private end use organisations - General interest in hydrogen economy	Manufacturers – low response rates to formal surveys; most data deemed to be commercially sensitive (small market, easy to identify source) End users (general) – highly varied in nature and size; not willing to share data relevant to consumption and appliances in use; low response rate to formal surveys; are already planning decarbonisation using currently available alternatives

Engagement with Commercial sector stakeholders for this study was found to be extremely difficult. As discussed further later in the report, there is currently no 'push' or 'pull' towards a hydrogen economy, and therefore most stakeholders are waiting to see developments before committing any time, resource or capital. The engagement process often involved positive initial contact with stakeholders, clearly interested in the Hy4Heat programme and wider hydrogen economy developments, but rarely lead to a sharing of more detailed information, most notably with the end users.

FEA noted that catering appliance manufacturers do not see conversion to hydrogen as an immediate issue, relative to their current development timelines, and therefore rely on FEA to represent them on such matters. This was evidenced by the low response rates for the initial and follow-up manufacturers' surveys.

3.3 Data Analysis

One of the key activities for market research as part of WP5 was an extensive Freedom of Information (FOI) campaign to obtain data related to gas appliances installed in public sector organisations. The volume of data obtained, and the varied format in which it was received, presented a challenge for data handling and quality.

Data sets were analysed in a hierarchical approach:

- Can the data help answer/ add context to a project objective?
- Is the data in a 'clean' and usable state?
- Does the data meet a minimum threshold for completeness?

Where a data set was deemed to meet the above criteria, the data was extracted and transferred to the central database, at which point various quality checks were carried out to ensure errors were captured and corrected. Statistical analysis of the data highlighted outlier values for priority checking, and data sets with small sample sizes where errors could have the biggest potential impact.

A customised dashboard was developed to help visualise the data. Further details are provided in Section 4.5.3.2

3.3.1 Model Development

A model for estimating the overall cost for converting the Commercial sector to 100% hydrogen has been developed. On completion of the input data gathering and analysis, the relevant inputs were entered into the model to generate the overall cost estimate. To account for any potentially significant gaps in knowledge, the model allows for key inputs to be entered as a range, with Monte Carlo assessment to determine the sensitivity of the overall cost estimate to each input. For more information, refer to Section 7.

4. UNDERSTANDING THE COMMERCIAL SECTOR

This section of the report describes the commercial sector and defines what is considered to be 'commercial' for the purposes of this study. A summary of the end use settings within the commercial sector and their relative natural gas consumption is provided, along with the typical gas appliances installed for the main uses of natural gas in the commercial sector - heating, hot water and catering. Estimates of the installed base for the major appliances are provided, along with an indication of the distribution of appliances across the various subsectors and end use settings where possible.

4.1 What is 'Commercial'?

The definition of 'Commercial' is not fixed when referring to gas usage. Depending on who is being consulted, the differentiation between domestic and commercial can be different. This is evident from responses provided in discussions with appliance manufacturers, who noted the two main differentiators as:

1) Appliance output; and
2) Appliance end use/setting.

For the purposes of this study, both differentiators are used in the definition of 'commercial'. A brief summary of each differentiator and how it is applied is provided in the following sections.

Other definitions for 'commercial' are also used by various organisations. For example, gas distribution network operators (GDNOs) use metrics related to gas consumption patterns (e.g. time of day, peak rate, etc.) to differentiate between domestic and commercial users. However, this is largely to help address security of supply issues for commercial users, and does not provide any direct indication of the type of commercial premise where the gas is being consumed.

Annual consumption is sometimes used to differentiate between domestic and commercial premises. Figures in the order of 25-45 kWh per year are given as indicative annual gas consumption for small to medium sized businesses. However, a large house with multiple bedrooms and poor insulation can easily exceed 25 kWh annual consumption, therefore making consumption alone an unreliable differentiator for domestic versus commercial premises.

4.1.1 Appliance Output

The rated output for heating appliances has several thresholds for consideration as to whether it is commercial. The vast majority of boilers up to 30 kW are found in domestic settings, and for that reason 30 kW is often taken as the lower limit for commercial. This is reflected in the statistics held by the relevant trade association, the Industrial and Commercial Energy Association (ICOM), which keeps statistics of appliance sales 30 kW and above. As such, 30 kW is used as the lower threshold for commercial boilers in this study.

The other key lower threshold for boilers is 70 kW, at which several aspects of the appliance design, testing, installation, maintenance and inspection diverge from those for domestic appliances. Boilers with a nominal heat input of over 70 kW are subject to a different design standard (BS EN 656) and the Institute of Gas Engineers and Managers (IGEM) produce a number of Technical Standards for boilers in a commercial/industrial setting.

For commercial water heaters, ICOM collect data for appliances with a recovery rate of 300 L/hour and greater at 50°C rise. This is taken to be the lower limit for commercial use for the purposes of this study.

Commercial gas-fired warm air heaters are specifically designed for use in commercial and industrial settings. They start as small as 10 kW per unit and go up to 1,000 kW per unit. Only a limited number of domestic variants are available in the UK, and these units are typically in the range of 10 – 50 kW. No minimum threshold is applied to warm air heaters in the context of this study as it is considered reasonable to assume that all commercial gas fired warm air units sold in the UK are installed in commercial or industrial settings.

Similar to warm air heaters, gas fired radiant heaters are specifically designed for use in commercial and industrial settings. Units start at 5 kW for radiant plaque (luminous) and 10 kW for radiant tube (non-luminous) and go up to 50 kW and 60 kW respectively. No lower threshold is applicable since all commercial units sold in the UK are considered to be installed in commercial and industrial settings.

Commercial catering appliances are generally larger with higher output ratings than their domestic variants, where they exist. Whereas domestic appliances are only required to cook up to three meals per day for a typical family, commercial appliances must to be able to cook many more meals over the course of the kitchen’s opening hours. In addition, they are generally required to cook food faster and more efficiently than a domestic appliance. However, given the range of appliance outputs across the various commercial appliance types, and that the difference in output ratings between domestic and commercial cooking appliances is relatively small, no minimum thresholds have been specified for this study. Truly commercial appliances are produced by manufacturers specialising in commercial appliances rather than domestic appliances, and as such the sales data and industry knowledge of the members of the relevant trade association is relied upon to inform this study.

4.1.2 Appliance End Use/Setting

Energy consumption statistics in the UK are reported under four main sectors – transport, domestic, industry and ‘service’. The ‘service’ sector includes agriculture, public administration and commerce [1]. For the purposes of this study agriculture is excluded, as its contribution to service sector natural gas consumption is less than 1.5%.

Public administration and commerce, hereafter referred to as the commercial sector in this report, are characterised by the following sub-sectors:

- Community, Arts and Leisure (CA&L)
- Education
- Emergency Services
- Health
- Hospitality
- Military
- Offices
- Retail
- Storage

The commercial sector can also be split into ‘public’ and ‘private’ based on the ownership of the business operating within the premise. Using the definitions provided in the BEES report [3], public sector includes all premises from the health, education, military and emergency service sub-sectors, excluding private hospitals and private schools, and includes public sector offices. Health centres are ‘majority public sector’ and leisure centres and nurseries have been identified as ‘mixed’. All other premises are considered to be private sector.

The distinction between ‘public’ and ‘private’ is less significant in terms of gas consumption than it is for the purchase and maintenance/replacement of the appliances. Small private businesses may only own a single appliance for which they will happily pay for maintenance and repairs for as long as possible. Large public and private organisations are more likely to own a stock of appliances serving their premises which they may replace more frequently as economy of scale and gains in efficiency allow for significant cost saving. Public sector end users may also be more likely to replace appliances more frequently in order to limit emissions in line with government targets.

Other work packages in the Hy4Heat programme are specifically looking at domestic and industrial appliances, in WP4 and WP6, respectively. It is noted that there is potential overlap between the appliances covered in both of these work packages and those in WP5.

As described in the study scope, WP5 is investigating all hot water space heating appliances up to 1MW. Industrial end users, whilst also consuming large quantities of natural gas for various processes, also consume considerable quantities of natural gas for space heating and domestic hot water. Often this is achieved with commercial sized heating appliances, and as such, gas-fired space heating appliances < 1MW in the industrial sector are also considered in this study.

The major sub-sectors of the commercial and industrial sectors are presented in Table 4-1 – Example End Use Settings for Commercial and Industrial Sectors along with examples of end use settings and their relative size.

Table 4-1 – Example End Use Settings for Commercial and Industrial Sectors

Sub-sector	Example End Use Setting – Small	Example End Use Setting – Large
Community, Arts and Leisure (CA&L)	Theatres Clubs and community centres	Holiday parks with sub-tropical heated environments, swimming pools, etc.
Education	Nurseries	State Primary Schools, State Secondary Schools
Emergency Services	Law Courts Police, Fire and Ambulance Stations	Prisons
Health	Health Centres	Hospitals
Hospitality	Local café / take away occupying single retail unit/ converted former domestic dwelling	Hotels with mass-catering facilities
Military	Military offices and civilian accommodation	Military storage
Offices	Small office spaces	Large office blocks
Retail	Local beautician/ hairdressers, etc. occupying single retail unit/ converted domestic dwelling Corner shop, typically found in village centres, towns and cities	Supermarkets Shopping centres (i.e. not high street), typically few in number in major cities
Storage/ distribution	Local self-storage facility with single office and lock-ups accessible by customers upon request.	Warehouses used as distribution centres for freight companies, retail stores, Internet shopping retailers, etc.
Industrial	Workshops	Factories

Commercial catering is similarly varied, and catering activities are not only confined to the Hospitality subsector (e.g. pubs, restaurants, cafes), but are also present in every other commercial and industrial subsector to some extent. The catering industry uses the following sectors and groupings to differentiate food preparation:

- Profit or commercial sector: outlets which have to cook dishes in a short time (includes restaurants, quick service, pubs, hotels and lodgings and leisure).

- Cost or non-commercial or institutional sector: outlets which have to cook large amounts of food and serve at scheduled times (includes staff catering, health care, education and services).

These sectors are defined in more detail in Table 4-2.

Table 4-2 – Typical Food Service Outlets for Commercial Catering Appliances

Category	Details	
Restaurants	European Ethnic	Other including In-Store, Roadside Restaurants, Pizza
Quick Service	Fast Food Cafes	Take Aways
Pubs	Tenanted and Leased Managed Branded Managed Unbranded	Freehouse Wine Bar Night Club
Hotels and Lodging	Hotels Bed and Breakfast Holiday Camps	Youth Hostels Caravan Parks
Leisure	Visitor Attractions Entertainment Clubs	Events and Mobile Caterers On Board Travel
Staff Catering	Self-Run Canteens Contracted Canteens National Government Canteens	Local Authority Canteens / Civic Centres Offshore Catering
Health Care	State Hospitals Independent Hospitals	Care Homes
Education	State Schools Independent Schools	Further / Higher Education
Services	Police Stations Fire Stations Armed Forces Prisons	Young Offenders Institutions Welfare Services Voluntary Services

At this point, it is worth highlighting the large variation in end users within the commercial sector. Standardised Industrial Classification (SIC) [2] uses 21 sections, 88 divisions, 272 groups, 615 classes and 191 subclasses to classify business establishments by the type of economic activity in which they are engaged. Commercial sector activities are relevant to approximately two thirds of the sections (industrial activities account for the other third).

The Building Energy Efficiency Survey (BEES) study [3] revealed that the non-domestic stock in England and Wales comprises approximately 1.83 million premises. No source was identified for the stock of non-domestic premises for the entire UK. However, on the basis that England and Wales make up 89% of the population of the UK[1], 90% of VAT and/or PAYE based local units[2], and 91% of

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[1] https://en.wikipedia.org/wiki/Countries_of_the_United_Kingdom_by_population

[2] https://www.ons.gov.uk/file?uri=%2fbusinessindustryandtrade%2fbusiness%2factivitysizeandlocation%2fdatasets%2fukbusinessactivitysizeandlocation%2f2019/ukbusinessworkbook2019.xlsx

non-domestic property transactions[3], the assumption to divide the BEES stock by 90% to derive a total UK stock of 2.03 million non-domestic premises is considered reasonable.

The variation in Commercial premises, in type and number, is in stark contrast to the domestic sector (nominally less than ten types of dwelling for space heating classification purposes) and the industrial sector (nominally 12 heating appliance types used across 12 main processes).

4.2 Commercial Sector Energy Usage Statistics

'Energy Consumption in the United Kingdom' (ECUK) [1] is an annual statistical publication that provides a comprehensive review of energy consumption in the UK. This study relies on the usage data presented in ECUK, and unless stated otherwise, is the basis for energy consumption data presented in this report.

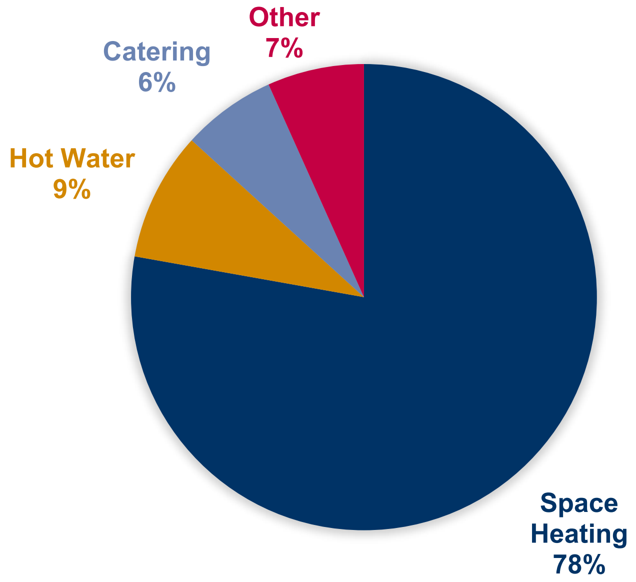
In 2017, commercial sector natural gas usage in the UK totalled 91.2 TWh. Including space heating in the Industrial sector, natural gas consumption rises to 103.6 TWh. This is compared to 297.0 TWh for domestic and 84.1 TWh for industrial (excluding space heating).

For the commercial sector the significant uses of natural gas are:

- Space heating of buildings;
- Hot water (for sanitary uses); and
- Catering.

The relative split of natural gas consumption in the ECUK data for 2017 for space heating, hot water, catering and 'other' (e.g. pools, CHP) is shown in Figure 4-1.

Figure 4-1 – Major Contributors to Commercial Gas Consumption



The largest consumers of natural gas in the commercial sector are the Health (18%), Education (15%), Offices (13%), Industrial (12%) and Community, Arts & Leisure (12%) subsectors, as shown in Figure 4-2. The two largest consumers are largely made up of public sector end users (e.g. hospitals and schools).

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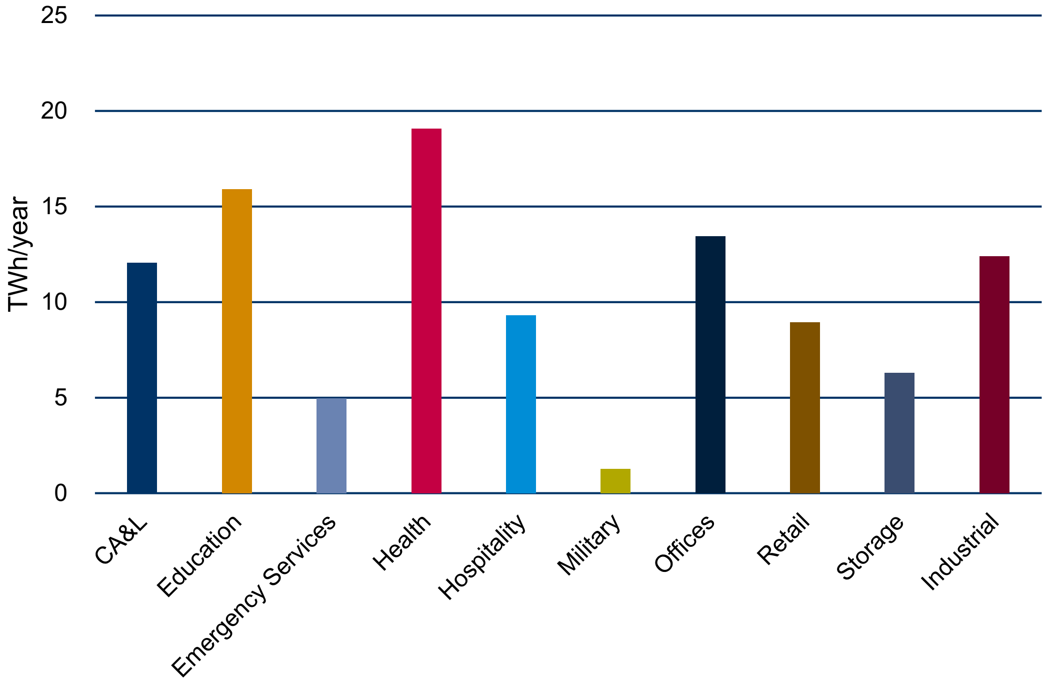
[3] https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/771859/UK_Tables_Jan_2019__cir_.pdf

Figure 4-2 – Commercial Gas Consumption by Subsector



4.2.1 Space Heating

Natural gas is the largest fuel source for space heating in the commercial and industrial sectors, representing more than 55% of the annual energy consumption of 6,931 thousand tonnes of oil equivalent (ktoe), or 80.6 TWh, in 2017.

The subsectors with the highest natural gas consumption for space heating are Education, Industrial and Offices. Individually, the end use settings with the highest consumption of natural gas are Private Offices (12.6%), Hospitals (12.4%) and Factories (12.0%).

4.2.2 Hot Water

As with space heating, natural gas is the largest fuel source for hot water in the commercial and industrial sectors, at nearly 9.3 TWh in 2017.

Hospitals are by far the largest consumers of natural gas for hot water in the commercial sector, accounting for 38% of total consumption, followed by Hotels (8.2%), State Primary Schools (7.7%) and State Secondary Schools (7.6%).

4.2.3 Catering

Whereas natural gas is the dominant energy source for space heating in the commercial and industrial sectors, electricity is the dominant energy source for catering, with 9.0 TWh consumed in 2017 compared to 6.7 TWh of natural gas. Natural gas was the main energy source in only three subsectors, namely CA&L, Education and Health.

The largest end users of natural gas for catering are Restaurants & Takeaways (1.56 TWh), Pubs (1.55 TWh) and Hospitals (0.61 TWh). The largest of these, Restaurants & Takeaways, is actually more reliant on electricity (3.82 TWh) as its main energy source for catering.

Gas consumption is linked to the number of food service outlets and number of meals served. Data published as part of preparations for the Ecodesign Directive reveals the number of food service outlets and number of meals served by each for 2006 [4]. This data is summarised in Table 4-3 to give an indication of the relative prevalence and meal production intensity of each food service outlet type.

Table 4-3 – UK Foodservice Outlets (2006)

Foodservice outlets	Number of foodservice outlets (in thousands)		Number of meals served (in millions)	
Restaurants	26.6	10%	750	9%
QSR (Quick Service)	29.8	11%	2,034	23%
Pubs	51.0	19%	1,125	13%
Hotels	46.6	18%	645	7%
Leisure	19.2	7%	537	6%
Staff Catering	20.4	8%	1,061	12%
Health Care	31.6	12%	1,050	12%
Education	34.6	13%	1,230	14%
Services	3.1	1%	249	3%
Total UK	**262.9**		**8,682**	

Source: Lot 23 [4].

The data presented in Table 4-3 is presented as a guide only due to its age. It is known that a significant number of pubs have closed since 2006, with one source [5] putting the number at close to 10,000. However, it is not known exactly what impact that has on the number of food service outlets, as not all pubs serve food.

4.3 Natural Gas Heating Appliances in the Commercial Sector

4.3.1 Space Heating

Space heating is necessary to satisfy the thermal comfort requirements of building occupants, most notably in winter months when ambient temperatures can remain below the range in which occupants feel comfortable for extended periods. Energy for space heating is the largest consumer of natural gas in the commercial sector.

Within the commercial sector there is a wide variation in the volume of space which requires heating, from small, single room retail spaces in the order of 100 m^2 to distribution centres, prisons and hospitals with floor spaces in excess of 20,000 m^2.

Specific design issues that must be considered when selecting the appropriate space heating appliance include:

- Spot heating versus zone heating
- Importance of balanced heating (i.e. wall to wall and floor to ceiling)
- Air change rates within the space requiring heat

- Air quality and ventilation requirements
- Acceptable noise levels
- Location of the heating unit.

Despite the variation across and within commercial subsectors and the above design considerations, the number of gas fired heating appliance types is relatively small, and can be represented by the following:

- Wet system
    - Boilers (traditional, wet central heating systems)
- Dry (warm air) system
    - Direct air heaters
    - Indirect air heaters
- Radiant heating
    - Luminous (plaque)
    - Non-luminous (tube)
- Heat pumps (gas engine driven)
- Combined Heat and Power (CHP) plants.

Table 4-4 - Typical Commercial Space Heating Appliances and Outputs

Application	Category	Appliance	Typical Output Range (kW)
Space Heating	Wet Systems	Condensing Boiler (pre-mix burner, wall hung)	30-150
		Condensing Boiler (pre-mix burner, floor standing)	30-1,000
		Condensing / Non-Condensing Shell Boiler (package, pressure jet burner)	400 - >1,000
	Dry (Warm Air) Systems	Direct Air Heater	10-150
		Indirect Air Heater (‘Cabinet’, floor standing)	15-1,000
		Indirect Air Heater (‘Unit’, suspended)	15-150
	Radiant Heating	Luminous (Plaque) Heater	5-50
		Non-Luminous (Tube) Heater	15-60
	Heat Pumps	Gas Engine Driven Pump	20-200

4.3.1.1 Boilers

Space heating in the commercial sector is largely provided by boilers. Commercial boilers are very similar to their smaller (domestic) and larger (industrial) equivalents. Simplistically, each boiler consists of a gas-fired combustion chamber, from which hot flue gases are fed to a water-filled heat exchanger. The design and layout of boilers tends to follow some familiar blueprints for wall hung, floor standing and shell variants.

The choice of the most appropriate boiler for specific applications depends on:

- Temperature of water required
- Pressure of water required
- Volume of water being heated
- Demand profile and modulation requirement (i.e. peak demand versus base load)
- Available space
- Infrastructure available for ventilation of flue gases.

Individual commercial units can largely vary in size and heat input from 30kW to considerably more than 1,000kW. Boilers up to approximately 150kW can be wall hung, with internals very similar to domestic boilers (although development and testing can be very different; see Section 5.3). Above 150kW, boilers tend to be floor standing due to weight restrictions.

Figure 4-3 – Wall Hung Condensing Boiler

Source: https://idealcommercialboilers.com

Figure 4-4 – Floor Standing Condensing Boiler

Source: https://www.hoval.co.uk

Many commercial boiler designs also provide the option of “cascading”, where a bank of smaller units are linked to meet a much higher demand. For example, to meet a peak demand of 500kW, five units of 100kW each are installed with a control system to sequentially turn individual boilers on or off depending on demand. Spreading the required heat load over several smaller boilers provides greater reliability, increased operating flexibility (larger turndown ratios) and higher efficiencies. This type of installation has become more common in recent years, aided by more reliable and sophisticated control systems.

Figure 4-5 – Cascade Boiler System

Source: https://www.vaillant.co.uk/commercial/

Figure 4-6 – Shell Boiler

Source: https://www.bosch-thermotechnology.com/gb/en/commercial-industrial/home/

The Ecodesign for Energy-Related Products Regulations (ErP) [6] mandates that all boilers up to 400kW are condensing type to improve fuel efficiency. These boilers therefore have heat exchangers made of corrosion resistant materials to withstand condensation of flue gases. ErP does not apply to appliances above 400kW, and therefore boilers larger than this are not required to be condensing type. However, depending on the intended location of the boiler, Building Regulations L2A [7] and L2B [8] requirements for minimum efficiency levels may require that a condensing type is selected.

Many large capacity commercial boilers are described as ‘package’ boilers, where the boiler is supplied separately to the burner. The burner must be sourced from a ‘matching schedule’ of approved burners that are able to meet the rated performance values. Typically these package boilers are in excess of 400kW, have horizontal shell and tube type heat exchangers (‘shell boiler’), with forced draft pressure jet burners and multi-pass flue gas flow-paths.

Burners found in commercial boilers are a wide variety of forms and materials. The size and shape of the heat exchanger within the boiler body often dictates what type of burner can be used based on the cavity that remains in the combustion chamber. Common types of pre-mix burners include flat, cylindrical, conical and disc. These burners tend to be pre-mixed with a modulating fan to manage efficiency and emissions by careful control of the gas-to-air ratio. The flame is typically diffuse to increase stability and efficiency.

Larger capacity commercial boilers use a pressure jet burner to generate the higher heat outputs required. In such boilers, a large central combustion chamber accommodates the flame, with flue gas making several passes through the heat exchanger to increase efficiency before being exhausted via a flue.

4.3.1.2 Warm Air Heaters

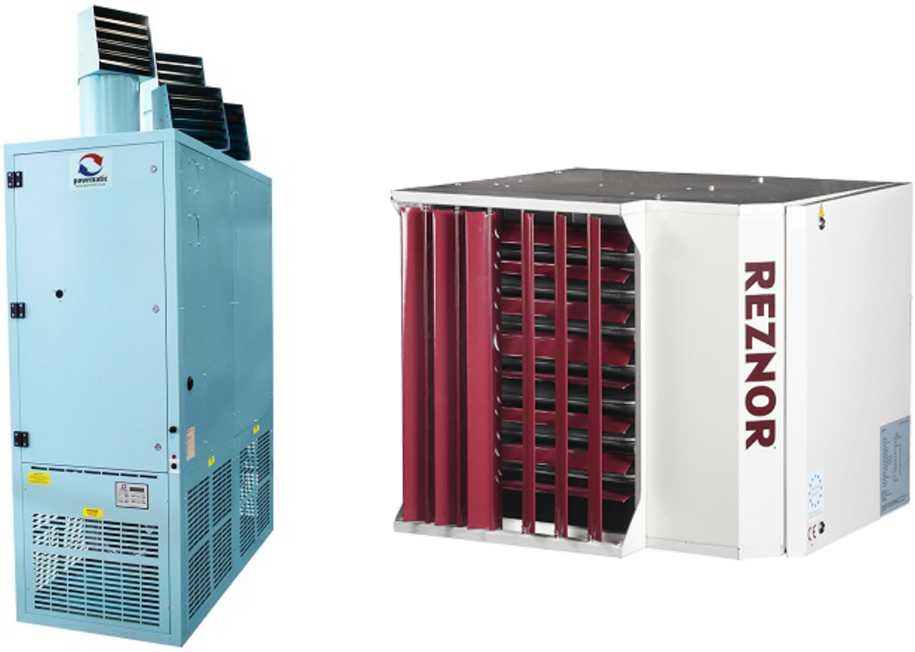
Warm air heating appliances are specifically designed to provide space heating by using the heat generated by a burner to raise the air temperature in the space(s) being heated.

In direct-fired warm air heaters, the heat generation by combustion takes place directly in the air stream circulating in the heated space.

With indirect-fired warm air heaters, the fuel is burned and the hot flue gas is passed through a heat exchanger that is installed inside the ventilation airflow. A fan draws in the surrounding air and passes it over the heat exchanger. The heat is transferred from the flue gas to the ventilation air. After passing the heat exchanger, the hot flue gas is extracted to the outside either by natural or induced draught.

Warm air heaters are often described as ‘unit’ (suspended from the ceiling) or ‘cabinet’ (floor standing).

Figure 4-7 – Cabinet Air Heater (left), Unit Air Heater (right)



Source: https://www.warmairheaters.com/

4.3.1.3 Radiant Heaters

Radiant heating appliances are specifically designed to heat people or objects in the space below them by infrared radiation without heating the surrounding air directly.

A radiant tube (non-luminous) heating system consists of a combustor for heat generation, linear or U-shaped steel tubes for heat transfer, a radiance reflector above the tubes and a fan for supporting the flow of the resulting flame and the hot flue gas through the tubes. The combustor, which is mounted on one end of the steel tube, produces a long flame with a length of up to 5 metres that reaches far inside the tubes. Therefore, the tube is heated by the long flame to temperatures of 300°C to 600°C. In this relatively low temperature range, the steel tubes do not emit visible light (glowing); the wavelength of the emitted radiation is about 5μm. With the help of the radiance reflectors above the steel tubes, the thermal radiation can be redirected to the ground in the heated space.

Luminous (plaque) radiant heaters contain gas nozzles that atomise the combustion gas into a venture nozzle. This injection causes the air needed for combustion to be automatically sucked in and mixed with the gas according to the Bunsen burner principle. One major advantage of this technique is that no additional fan is needed, causing luminous radiant heaters to work almost noiselessly. The gas-air mixture is led through the burner plate, which has several small holes (diameter approximately 1mm) and is ignited. The combustion process takes place in these holes, so that no direct flame can be seen. Because of this process, the surface of the ceramic plate is heated up to 950°C and starts glowing “luminously”. The wavelength of the emitted radiation is about 2.5μm.

Figure 4-8 – Radiant Tube Heater (top), Radiant Plaque Heater (bottom)

Source: https://www.warmairheaters.com/

4.3.2 *Hot Water*

Water heating in the commercial sector is primarily for the following:

- Drinking water
- Baths and showers
- Public/utility basins
- Swimming pool heating

Gas fired water heating appliances include direct fired storage heaters, circulating type heaters and instantaneous point-of-use heaters. Each type of commercial water heater shares similar design concepts and components to light commercial boilers.

The Ecodesign for Energy-Related Products Regulations (ErP) also applies to commercial water heaters, with new appliances required to meet limits for efficiency (usually requiring a condensing section) and emissions (e.g. NO_x).

Table 4-5 – Typical Commercial Hot Water Appliances and Outputs

Application	Category	Appliance	Typical Output Range (kW)
Water Heating	Wet Systems	Direct Fired Storage	30-150
		Circulating	30-600
		Instantaneous	30-60

Figure 4-9 – Direct Fired Storage Water Heater

Source: https://lochinvar.ltd.uk/

Figure 4-10 – Circulating Water Heater

Source: https://mediacdn.andrewswaterheaters.co.uk/

Figure 4-11 – Instantaneous Water Heater

Source: https:// https://www.rinnai-uk.co.uk

4.3.3 Catering

According to one major commercial catering manufacturer, there are 12 main ways to cook food, namely bake, boil, braise, deep fry, shallow fry, grill (from above), grill (from below), poach, roast, pot roast, steam and stew[4]. The types of appliances listed in European Standard EN 203 represents the range of gas fired commercial catering appliances typically found in commercial kitchens in the UK which perform one or more of the above cooking methods. The appliances are summarised in Table 4-6 with typical output ranges, and in Table 4-7 with their respective cooking functionality.

Ranges are often the 'prime cooking machines' in commercial kitchens due to their versatility, allowing for 10 of the 12 methods of cookery. In Table 4-6 they are considered by their main components, a convection oven plus 'solid' or 'open' top (i.e. hob).

Table 4-6 – Typical Commercial Catering Appliances and Outputs

Application	Category	Appliance	Typical Output Range (kW)
Catering	Steam Integrated Ovens	Combi-Steam Oven	10-50
		Atmospheric Steamer	10-20
	Hobs & Grills	Hob	3-6 (per burner)
		Griddle	10-25

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[4] https://www.falconfoodservice.com/InfoCentre/Advice/GeneralIndustryInformation/The12MethodsofCookery.aspx

Application	Category	Appliance	Typical Output Range (kW)
		Chargrill	10-40
		Salamander Grill	5-15
		Rotisserie Grill	10-50
	Water & Oil Heating	Fryer	10-25
		Pasta & Noodle Boiler	10-50
		Bratt Pan	10-50
	Ovens	Convection Oven	10-50
		Pizza Oven	10-50
		Deck Oven	30-150
		Rack Oven	70-110

Table 4-7 – Commercial Catering Appliances and Functionality[5]

	Bake	Braise	Roast	Pot Roast	Boil	Poach	Steam	Stew	Grill (above)	Grill (below)	Deep Fry	Shallow Fry	Total (of 12)
Range	X	X	X	X	X	X	X	X			X	X	10
Combi Oven	X	X	X	X	X	X	X	X					8
Hob				X	X	X	X	X			X	X	7
Bratt Pan		X			X	X	X	X			X	X	7
Oven	X	X	X	X				X					5
Boiling Pan					X	X		X					3
Steamer					X		X	X					3
Pasta Cooker					X	X	X						3
Salamander Grill									X				1
Chargrill										X			1
Fryer											X		1
Griddle												X	1

4.3.3.1 Steam Integrated Ovens

Steam Integrated Ovens are catering appliances that generate steam as means of transferring heat to cook food. Gas fired burners are used to produce steam, from which the condensate is then collected and disposed of after use. Steaming of food is often used as means of cooking large volumes of food with relative ease.

These appliances come in two main categories:

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[5] https://www.falconfoodservice.com/InfoCentre/Advice/GeneralIndustryInformation/The12MethodsofCookery.aspx

- Combi-Steam Oven – ovens which have the dual function of both a conventional convection and a steamer;
- Atmospheric Steamer – appliances capable of only cooking with steam.

4.3.3.2 Hobs & Grills

These appliances provide a heated surface for cooking through direct contact between the flame of a gas fired burner and a target surface. This target surface can be a:

- Pan – applicable to hobs;
- Plate – applicable to griddles and chargrills;
- Radiant plaque – applicable to salamander grills and rotisserie grills.

4.3.3.3 Water & Oil Heating

Appliances used for water and oil heating consist of a vessel containing the liquid being used as the cooking medium, which is heated via gas burners. Food is placed into the liquid, the heat of which is utilised to cook the food.

These appliances can be categorised as:

- Fryer – appliance which heats a volume of oil used for frying various foods;
- Pasta & Noodle Boiler – water is boiled by these appliances to cook large quantities of pasta, noodles and similar food types;
- Bratt Pan – an appliance that is used for boiling both water and oil, capable of braising, boiling, steaming, poaching, stewing, roasting and frying.

4.3.3.4 Ovens

Ovens generally consist of a confined chamber where food is placed on shelves, which is heated directly by gas burners. The main types of ovens found in commercial settings are:

- Convection Oven – the most “standard” oven, compared to those found domestically. Often heat transfer is assisted by a fan circulating the hot air;
- Pizza/Deck Oven – these appliances are heated on a shelf-by-shelf basis (if multiple units are being used) to deliver the correct proportion of top and bottom heat for cooking pizzas and similar food types;
- Rack Oven – this type of oven is similar in design to a Convection Oven, but generally used for cooking in large volumes. “Racks” of trays (stacks of trays stored vertically) are wheeled into these ovens where the heat is distributed evenly. They are very often used by bakeries.

4.3.3.5 Other Commercial Appliances

Other gas fired commercial catering appliances include kebab machines, tandoori ovens, rotisseries, barbecues, Chinese woks, chapatti hot plates and burger plates.

4.3.4 Exclusions

- Process appliances < 1MW such as industrial baking ovens, furnaces and kilns. This exclusion creates a potential coverage gap in the Hy4Heat program between WP5 and WP6.
- Steam boilers – included in the overall population data but not split out from ‘low temperature’ boilers and not considered further in the study.

- CHP – specifically excluded from the study scope.
- Bunsen burners; these are considered to be the most basic combustion appliance, with no forced aeration, heat exchanger or control devices. Hydrogen compatible bunsen burners are already available and therefore not considered further.

4.4 Alternative Low Carbon Heating Appliances in the Commercial Sector

The aim of the Hy4Heat program is to help the UK Government meet its commitment to decarbonise heating in the UK. Low carbon alternatives to the commercial appliances covered in this study already exist and may take a larger market share during the transition to net zero carbon heating. This section highlights the key low carbon alternatives to the major commercial gas fired appliances used for heating, hot water and catering.

4.4.1 Space Heating and Hot Water

The Energy Saving Trust [9] provides information on methods for generating heat for homes with low-carbon, renewable technologies. Whilst the technologies discussed are intended for smaller heating loads in domestic dwellings, they could be applied to some larger heating requirements in commercial settings.

- Heat Pumps – working in reverse to a refrigerator, heat pumps upgrade ambient heat from air, ground or water sources to useful temperatures and have principally been developed for larger commercial buildings to date. Heat pumps can be gas or electric driven.
- Combined Heat and Power (CHP) Units – a gas driven internal combustion engine, Stirling engine or fuel cell linked to an electrical generator. Most of the energy that would be wasted as heat from the engine is recovered and used to power the heating system.
- Solar Water Heating (‘Solar Thermal’) – uses free heat from the sun to directly warm water.
- Biomass Systems – wood-fuelled burning systems burn wood pellets, chips or logs to provide warmth in a single room or to power central heating and hot water boilers.

Others low carbon alternatives include:

- Electric Boiler and Water Heaters (renewable source). Suitable for light commercial loads, but not heavy. Electric boilers are more efficient, however gas is cheaper to run and heats water faster.
- Transpired Solar Collectors. Air heating systems made of pre-finished perforated steel skins installed onto south-facing walls or roofs creating a cavity between the metal skin and the walls or roofs. The heated air can either be distributed into the building or ducted to a HVAC unit to reduce the energy required by the main heating system [10].

4.4.2 Catering

Low carbon alternatives to catering appliances exist in the form of electric appliances, where the electricity is provided from low carbon sources. Feedback from industry is that electric appliances are already more common than gas, due largely to the tendency for electric appliances for light cooking/heating loads. This is reflected in the energy consumption statistics, where it can be seen that electricity consumption is greater than natural gas consumption for catering over the whole sector, and in particular the entire Hospitality subsector with the exception of Pubs.

Several commercial catering industry stakeholders noted a recent trend away from natural gas appliances to electric. This trend has been attributed to several reasons:

- Simpler installation, with no additional safety and ventilation installation requirements, less maintenance and inspection.

- Popularity of induction hobs. It was noted that they are more expensive than equivalent gas hob, however they deliver superior efficiencies, increased safety (no naked flame or hot surfaces) and are easier to clean.
- Increased awareness of sustainability issues causing installers/end users to move away from fossil fuels.

At this point is it is worth highlighting that the commercial catering industry does not believe that full electrification of commercial kitchens is feasible. In urban areas it is common to have a 100 amp 3 phase supply to a commercial building; however, this is to supply the whole building so it is unlikely that the full capacity will be available for the kitchen. Furthermore, 100 amps per phase is only sufficient for a very small kitchen, with most commercial kitchens requiring between 160 and 200 amps per phase. For these reasons it is often the case that one or two items of gas equipment are included, usually combination ovens and fryers as the electrical versions require a lot of power.

Even if the end user is prepared to pay to have the electrical supply increased, it is not always possible to get it, as the power may just not be available in the area.

4.4.3 New Commercial Scale Applications for Hydrogen

In addition to existing alternative low carbon heating appliances, and the development of hydrogen variants of the most commonly installed natural gas appliances, some new commercial scale applications for hydrogen usage are being developed.

- Hydrogen micro CHP (mCHP) has the potential to deliver both heat and electric power requirements to small commercial premises using hydrogen for combustion.
- Hydrogen fuel cell CHP (FC CHP) has the potential to deliver both heat and electric power requirements to small commercial premises using hydrogen as a feed for fuel cells.

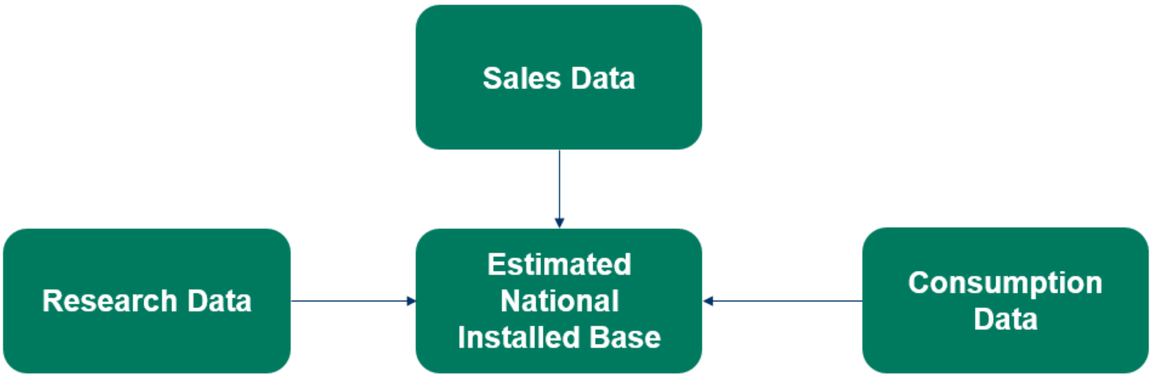
4.5 Commercial Sector Appliance Counts and Demographics

4.5.1 Approach

A literature review of previous estimates of commercial gas fired appliances in the UK highlighted the lack of detailed publicly available data. Notable studies have been completed in preparation for the Gas Appliances Regulations (GAR) in 2005 [11] and the Ecodesign Directive. However, these studies were limited in terms of their inputs and outputs to some degree, and justified a more thorough market estimate in order to support the Hy4Heat program's objectives.

A multi-angled approach is taken to obtaining relevant data in order to gain the most confidence in the commercial appliance population estimates. The approach is summarised in Figure 4-12 and described below.

Figure 4-12 – Approach to Estimating National Installed Base of Appliances



Sales Data

The key input for estimating the population of installed appliances is sales data from the relevant trade bodies. Sales data can be combined with knowledge of typical life spans of appliances to estimate the installed base count. Where aggregated sales data was incomplete or unavailable, population estimates were sought from manufacturers based on their own sales data and understanding of the market.

Bottom-Up Estimate

To supplement the population estimates obtained via sales data, appliance data obtained from FOIs is used to provide some insight into the relative distribution of appliances within the various sub-sectors and end uses. Appliance counts from the organisations that did respond and were deemed suitable (see Section 4.5.3) were extrapolated to estimate the total number of appliances installed in the relevant sub-sector and/or end use setting on a ‘bottom-up’ basis.

Where the response sample size was large (e.g. Hospitals and Fire and Ambulance Stations) a greater level of confidence can be taken versus subsectors and end use settings with very little or no coverage in the FOI data. However, even for sub-sectors with large numbers of responses there still exists some uncertainty and potential error, with no formal assessment of the samples’ statistical significance conducted, and FOI data being submitted in varying levels of quality. Further details of the bottom-up estimates are provided in Section 4.5.3.2.

FOI data is only relevant to public sector end uses, and therefore data gathering for appliances installed in private sector end uses relies more on direct engagement with end users, facilities management companies, etc.

Top-Down Estimate

Where no data was available for estimating installed appliance counts from sales data or actual installed counts, a ‘top-down’ estimate is made based on actual natural gas consumption for the subsector/end use setting. This estimate requires a number of assumptions and judgements to be made for each of the subsectors and/or end use settings. As such, these estimates must be considered to contain a significant degree of uncertainty, and are intended only to be used as a guide.

Full details of the top-down estimate process, inputs and assumptions are provided in Appendix B and summarised below:

- Natural gas consumption for space heating by subsector and end use setting
    - ECUK statistics (consumption data for 2017) [1]
- Subsector and end use premises details (count, footprint, % footprint heated by gas)

  - BEES data [3], supplemented by other sources where required
- Boiler 'usage factor' based on typical equivalent hours of full load operation
  - CIBSE Guide F [12], values provided for different building types
- Split of wet versus dry space heating (i.e. boiler versus warm air / radiant heaters)
  - Calculated from FOI data where available, or assumption/judgement
- Average boiler output capacity
  - Calculated from FOI data, ICOM sales data (i.e. 133 kW), or other source as relevant

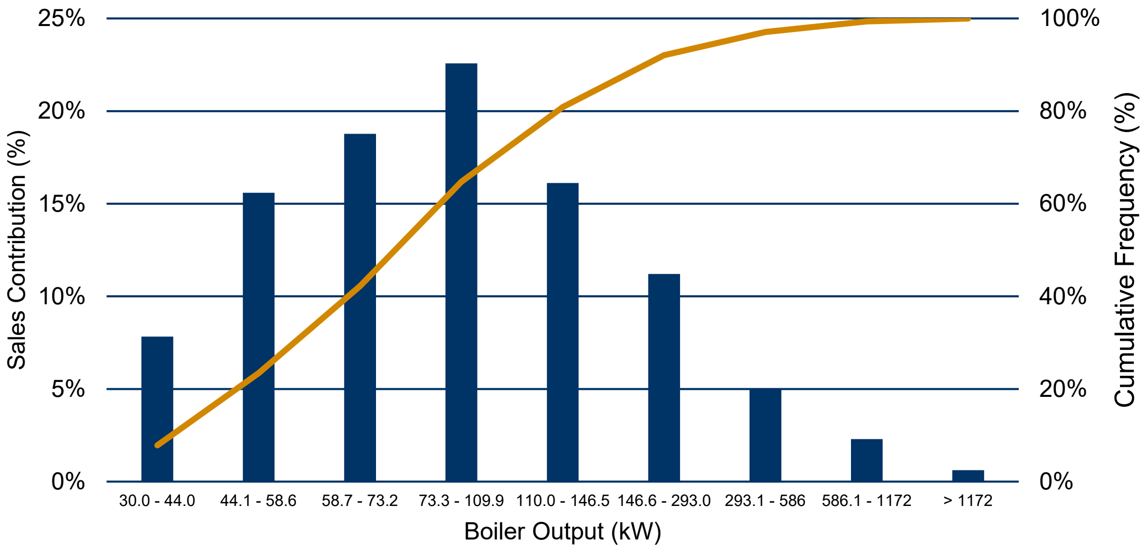
4.5.2 Estimates for Total Installed Population

4.5.2.1 Boilers

The installed base of commercial boilers and hot water appliances is based on sales data provided by ICOM. ICOM reports that its members represent almost all commercial boiler and water heater manufacturers selling in the UK, and therefore these figures can be treated with a high level of confidence.

Monthly sales figures are recorded in 'bins' of output capacities, anonymised and aggregated to produce annual sales figures. A summary of the annual sales figures is provided in Figure 4-13.

Figure 4-13 – Commercial Boiler Sales in the UK



Source: ICOM sales data 2019

Approximately 28,000 commercial boilers are sold in the UK annually. To put this in context, this figure is less than 3% of the number of domestic boilers sold in the UK each year (approximately 1.6 million).

Feedback from industry is that the typical life span of commercial boilers is 18 years. Applying this equally to all boiler output ranges gives a total installed base of **504,000** commercial boilers in the UK, where a commercial boiler is classified based on output equal to or greater than 30kW.

If the typical life span of all commercial boilers was assumed to be 15, this would equate to an estimated installed base of 420,000. Alternatively, if the typical life span was assumed to be 20 or 25 years, the estimated installed base would be 560,000 and 700,000, respectively. It is not considered credible that the average life of all commercial boilers could be 25 years, and therefore 560,000 based on an average life of 20 years is considered to be the credible 'high' estimate for commercial boilers.

A more tailored estimate of installed base can be made by applying a life span to each of the main types of boiler. This takes account of the differing design codes, typical warranties, replacement costs, etc. which may impact on the decision to repair or replace. The assumptions used for this estimate are summarised in Table 4-8.

Table 4-8 – Estimated Life Span for Commercial Boilers

Boiler Type	Life Span (years)
Wall Hung (<70kW)	12
Wall Hung (70-150kW)	15
Floor Standing (150-1,000kW)	20
Floor Standing (>1,000kW)	25

The installed base of commercial boilers is estimated to be 412,500 using the tailored average life spans as shown in Table 4-8. This is considered to represent the credible 'low' estimate for the installed base of commercial boilers in the UK.

Table 4-9 – Total Installed Commercial Boilers in UK

Estimate Type	Installed Base	Basis
Low	412,500	Sales data and average life span 12-25 years (by output)
Medium	504,000	Sales data and average life span 18 years
High	560,000	Sales data and average life span 20 years

The 'medium' estimate of 504,000 was presented at an ICOM meeting of boiler and hot water manufacturers, where members were asked to provide feedback on the estimate using semi-quantitative responses. Nearly half responded 'About right (± 10%)' and just over half responding 'Higher (10-50% more)'. Given the nearly equal split, it is thought that the values for 'Medium' and 'High' presented in Table 4-9 are appropriate and carried through to the cost model with Monte Carlo assessment.

Boiler Output Distribution

The most common commercial boiler size in terms of sales in the last 12 months is in the range 73.3-109.9kW, representing 23% of sales. The weighted average output for all commercial boiler sales is 131kW per appliance.

ICOM sales data does not explicitly reveal the split of wall-hung versus floor standing boilers, nor does it detail how many units were sold as part of a cascade system. Using the assumption that all commercial boilers up to 150kW are wall hung, then it could be estimated that 408,000 units (i.e. 81%) are wall hung. However, this is likely to be an overestimate given that many floor-standing units are also available in capacities less than 150kW. By extension, it can be concluded that at least 20% of boilers (96,000) are floor standing (i.e. greater than 150kW output).

Feedback from individual manufacturers estimates the number of boilers being sold as part of a cascade system as between 50% and 70% in the past 12 months; however, this percentage has not been verified by the wider industry.

Approximately 97% of boilers sold in the last 12 months are less than 400kW, meaning they must be condensing boilers in order to comply with the eco-design regulations. ICOM point out that approximately 3% of total sales in the past 12 months were for non-condensing boilers.

At the time of writing this report, there was no indication of the split of boilers with pre-mix burners versus shell boilers with package burners in the sales figures. However, on the assumption that all boilers > 400kW are shell boilers packaged with pressure jet burners, then 3% of the installed base (i.e. 15,000 boilers) are estimated to be pressure jet package boilers. It is noted that there are pre-mix boilers much larger than 400kW, and some pressure jet boilers smaller than 400kW; taking the threshold of 400kW is considered to be a reasonable split.

A comparison of boiler output distribution for ICOM sales data and FOI data is provided in Section 4.5.3.2.

Boiler Distribution within the Commercial Sector

ICOM sales data, and indeed responses from individual manufacturers, did not provide any indication of the distribution of boilers across the various subsectors and end use settings. To fill this gap, sales data was supplemented by two additional methods for estimating installed base:

- bottom-up estimates using data for actual installed appliances from FOI requests; and
- top-down estimates based on gas consumption data and assumptions for typical usage.

The results of the top-down estimate for boilers and warm air/radiant heaters are provided in Appendix B. As discussed previously, top-down estimates are based on a set of assumptions and judgements which require further validation and therefore should be treated with a significant degree of uncertainty, especially for private sector end uses.

Based on the top-down estimates, the total installed population of commercial boilers is estimated to be 497,000. This total is very close to the medium estimate using boiler sales data and life span estimates.

The largest park of commercial boilers are expected to be in the Retail (147,000), Education (77,000) and CA&L (68,000) subsectors. The top five end use settings in terms of number of installed boilers are estimated to be:

1. Small Shops
2. Offices (Private)
3. State Primary Schools
4. Places of Worship
5. Workshops

The Retail (Small Shops) end use setting has by far the largest number of premises, accounting for approximately 33% of all non-domestic premises in the UK. However, BEES data shows that less than 40% of the floor space is heated by natural gas, and when combined with annual consumption data, derives an average heat demand of 5kW per premise. It is therefore expected that a significant portion of Small Shops' heating demand is met by domestic sized boilers rather than commercial boilers.

The results of the bottom-up estimate for relevant end uses based on FOI data are provided in Appendix C and summarised in Table 4-18. A comparison of the top-down and bottom-up estimates for those end use settings with data for both is provided in Table 4-10.

Table 4-10 – Comparison of Top-Down and Bottom-Up Estimates (Boilers)

End Use	Estimate (Top Down)	Estimate (Bottom-Up)	FOI Data Coverage
Clubs and Community Centres	19,870	39,002	1.4%
Fire and Ambulance	2,981	5,936	10.9%
Hospitals	9,305	7,349	21.1%
Leisure Centres	9,285	13,476	2.5%
Nurseries	8,081	14,462	1.4%
Police Stations	4,143	3,042	10.8%
Prisons	475	1,081	11.5%
Universities	12,079	10,124	3.7%
Primary Schools	35,575	44,883	3.1%
Secondary Schools	21,067	42,243	0.8%
Total	**122,861**	**181,598**	N/A

Table 4-10 shows a significant difference in the estimated boiler counts using the different methods. The bottom-up estimate is higher than the top-down estimate for the majority of end use settings, and provides a total nearly 50% greater than the top-down estimate. This may be attributable to some 'bias' in the bottom-up estimate where, for example, sites with large numbers of boilers were more likely to respond. However, it is noted that the end use settings with the smallest coverage in the extracted data provided the largest discrepancy between the two estimates. When excluding end use settings with less than 3% coverage in the extracted data, the difference between the two estimates falls to 12%. This gives greater confidence in the accuracy of the top-down estimates.

Other potential sources of discrepancy are the quality of the assumptions and judgements which underpin the top-down estimate, and how representative the extracted data is of the overall population for the bottom up estimate. For example, the bottom-up estimate for prisons, despite a coverage of over 10% in the extracted data, is more than 100% greater than the top-down estimate. One possible explanation is that the responding prisons consume far more natural gas on average than the other prisons, requiring more boilers per site. Alternatively, the assumed use patterns and/or split between wet and dry space heating appliances may be inaccurate.

As discussed previously, the diversity of commercial and industrial premises and their respective space heating requirements makes predicting boiler population data extremely difficult. However, given that the bottom-up and top-down estimates begin to converge with increased data coverage, and that the top-down estimate closely agrees with the estimate based on sales data, there is a high level of confidence that the installed base of commercial boilers is in the range 412,500 to 560,000.

Knowledge Gap: Commercial boiler counts and distributions within private sector end use settings.

Knowledge Gap: Relative distribution of boilers across the commercial and industrial subsectors and end use settings.

Trends

There are numerous market forces in action for commercial boilers. Increased energy efficiency measures within commercial properties such as improved insulation, as with domestic and industrial settings, is curbing peak heating demands. Guidelines such as CIBSE Guide F [12] provide ‘typical practice’ and ‘good practice’ energy demands for various building types, encouraging end users to reduce their space heating energy requirements.

Additionally, there is a trend towards cascade systems, where multiple smaller units are linked together through a control system rather than single large units. This has the impact of increased total unit sales, with the output distribution curve shifted to the left (i.e. increased share of smaller units being sold), whereas the total installed capacity remains the same (not accounting for changes to overall heat demand). There is no specific data to quantify the effects of the above; however, the appliance output distribution curve from FOI data is significantly different to that of the ICOM sales data, possibly showing the effect of increased prevalence of cascade systems (see Section 4.5.3.2).

4.5.2.2 Water Heaters

Similar to boilers, ICOM sales data is used to estimate the installed base of water heaters. Over a period of 12 months, 11,000 commercial water heaters were sold in the UK. The typical life span of a commercial water heater is 18 years, therefore installed base of **198,000** commercial water heaters is estimated in the UK.

There is less variation in commercial water heaters than commercial boilers, therefore applying high and low life spans of 15 and 20 years gives a range of 165,000 to 220,000 for total installed base in the UK.

Water heaters are typically grouped into bins of ‘hot water recovery rate’ in terms of litres per minute based on a 50°C temperature rise. These can be roughly converted to power output, but this largely depends on the efficiency of the individual units.

The most commonly sold unit is in the range 501-1,000 litres/hour (44% of sales) which has a median output of approximately 45kW. The weighted average water heater produces 820 L/hr, equivalent to approximately 50kW input.

Water heaters are similarly being installed in cascades of smaller units to handle wide variations in peak and base demand levels. One estimate from a water heater manufacturer puts the proportion of water heaters sold as part of cascade systems at 50%.

As with commercial boilers, the ICOM sales data and indeed responses from individual manufacturers, did not provide any indication of the distribution of commercial water heaters across the various subsectors and end use settings.

Water consumption is difficult to estimate across the subsectors and end use settings, and is heavily dependent on the number of occupants, which is subject to large variations over the course of a year. As such, no top-down estimate has been made for water heaters.

Knowledge Gap: Relative distribution of water heaters across the commercial and industrial subsectors and end use settings.

4.5.2.3 Warm Air and Radiant Heaters

ICOM does not record annual sales of warm air and radiant heating appliances in the same way that it does for commercial boilers and water heaters. Engagement with individual manufacturers was therefore the key source of data for estimating the installed base of these appliances.

It is estimated that there are 12,000 unit sales per year for each of warm air and radiant appliances, with a range of 15-30 year life span for warm air heaters and 10-30 years for radiant heaters. The range of installed base estimates for each appliance type based on this data is provided in Table 4-11.

Table 4-11 – Estimated Total Installed Warm Air and Radiant Heaters in UK

Estimate Type	Installed Base	Basis
Warm Air Heaters		
Low	120,000	Sales data and average lifespan 15 years
Medium	240,000	Sales data and average lifespan 25 years
High	360,000	Sales data and average lifespan 30 years
Radiant Heaters		
Low	120,000	Sales data and average lifespan 10 years
Medium	240,000	Sales data and average lifespan 20 years
High	360,000	Sales data and average lifespan 30 years

It should be noted that neither estimate for the installed base of warm air heaters or radiant heaters has been ‘validated’ with feedback from industry; estimates are based on sales data from individual manufacturers.

Similar to hot water heaters and boilers, no indication of distribution of warm air and radiant heaters within commercial and industrial subsectors or end use settings was available. Data obtained from FOI responses contained only approximately 2,000 appliances (i.e. less than 1% of the estimated installed base) and therefore no valid conclusions can be drawn from this for the general population. This is largely due to the fact that most FOI data was obtained from public sector end use settings, which show very little reliance on warm air and radiant heating (less than 9% of appliances reported in the extracted data).

The largest users of warm air and radiant heaters are expected to be private sector users, in particular the Industrial, Retail and Storage subsectors. Top-down estimates predicts more than 80% of warm air and radiant heaters are installed in these three subsectors. A summary of the top-down estimate for warm air and radiant appliance distribution is provided in Table 4-12.

Table 4-12 – Top-Down Estimate for Warm Air and Radiant Heaters in Commercial Sub-sectors

Sub-sector	Estimated Installed Base
Community, Arts & Leisure	32,000
Education	23,000
Emergency Services	7,000
Health	11,000
Hospitality	46,000
Military	12,000
Offices	22,000

Sub-sector	Estimated Installed Base
Retail	112,000
Storage	114,000
Industrial	259,000
Total	**637,000**

Several large end users were contacted during the engagement program, however none were willing to share consumption and appliance data to be able to validate the assumptions which underpin the top-down estimate.

The top-down estimate made no attempt to differentiate the use of either warm air or radiant heaters within the various subsectors and end use settings. This reflects the current state of knowledge in the public domain, and of the manufacturers and end users engaged during the study.

Knowledge Gap: Total installed, and relative distribution of, warm air and radiant heaters across the commercial and industrial subsectors and end use settings.

4.5.2.4 Commercial Catering Appliances

FEA - the Foodservice Equipment Association, formerly known as CESA – is the largest trade body representing commercial catering appliance manufacturers selling their products in the UK. By FEA's own estimates their membership contributes the majority of all appliance sales in the UK. However, FEA does not collate detailed appliance level sales statistics, and therefore estimates for the installed base of commercial catering appliances are much more difficult to obtain. The ability to define the 'typical' contents of the various commercial kitchen types is a challenging task. Input was sought from the trade association which represents commercial catering distributors (CEDA) and its members. However, the results showed considerable variation in responses for the types and average number of appliances in the various commercial kitchens. This was supported by anecdotal feedback of end users in the same food outlet types with varying preferences for fuel (gas versus electric) based on cost, performance and 'green' priorities.

A study of commercial kitchen energy usage [13] also highlighted variation in appliance types, numbers and models between kitchens within a chain of gastropubs serving the same menu items.

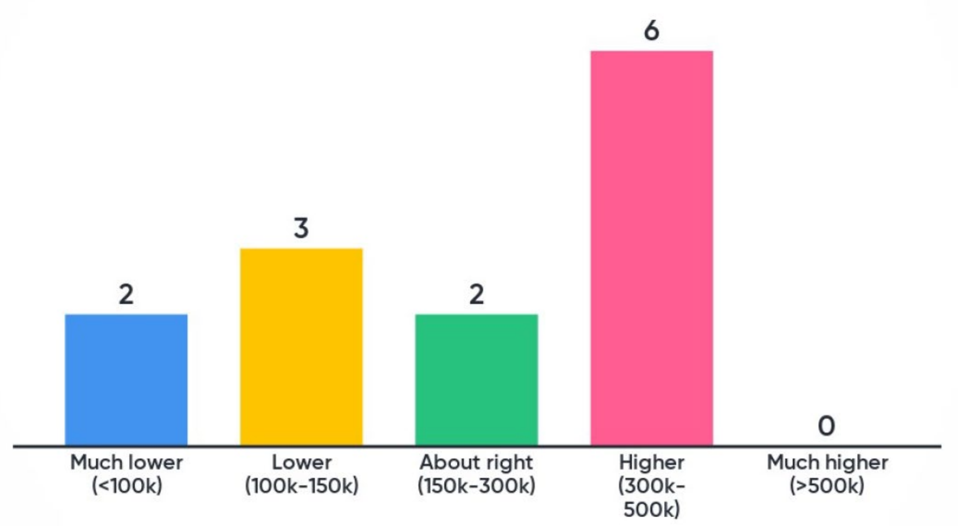
Independent consultancies such as Caterlyst collate data for food service outlets in the UK, including numbers of meals served by each type. However, the number of appliance types and commercial kitchen operations makes it almost impossible to estimate appliance numbers from consumption data (i.e. no top-down estimate can be readily developed). The commercial catering appliance sector is made more complex by the relatively large second-hand market for commercial kitchen appliances. At a meeting of FEA members in March 2020, attendees estimated that the second-hand market could contribute up to 25% of commercial cooking appliance purchases annually. This has been taken into account when estimating the total installed base of commercial appliances in the UK.

Data obtained by FOI for catering appliances was not extensive enough or of sufficient quality to draw conclusions. Appliance estimates in public sector kitchens can be further complicated by the fact that catering services are often subcontracted out, meaning that the tenant may not have responsibility for the kitchen and its contents to be able to provide accurate appliance data.

Given the above, it is not considered feasible to generate top-down or bottom-up estimates for commercial catering appliances.

Estimates for commercial catering appliances were derived from manufacturer input, based on knowledge of their own sales figures and their understanding of the size of the UK commercial catering market. These estimates have been 'played back' to FEA members for validation, initially via an online survey and later at a FEA members meeting in March 2020, using semi-quantitative indicators (e.g. about right ±10%, at least 50% higher, etc.). The response rate to the question of total installed gas commercial catering appliances was significant, and as such confidence in the estimated range of 150,000 – 400,000 is considered to be medium.

Figure 4-14 – FEA Members Survey Response – 'What is your opinion of the estimate of 200k gas fired commercial catering appliances in the UK?'



Using the revised overall estimate of the size of the gas fired commercial catering appliances market, the relative counts for each type of appliance was estimated based on input from the manufacturers. However, detailed input at the appliance level was not as readily available, and therefore confidence in the estimates for each appliance type is considered to be low.

Table 4-13 – Estimated Installed Base for Commercial Catering Appliances

Appliance Type	Estimated Installed Base in the UK
Combination Oven	4,000
Convection / Pizza Oven	3,000
Steam Oven	6,000
Bakery Oven (Rack / Deck)	10,000
Range	70,000
Hobs / Boiling Pans	12,000
Salamander Grill	30,000
Chargrill	20,000
Griddles	15,000
Bratt Pans / Boiling Units	10,000

Appliance Type	Estimated Installed Base in the UK
Fryers	50,000
Other (Kebab, Rotisserie, Tandoori Oven)	20,000
Total	**250,000**

FEA members do not supply a significant number of ovens for use in bakeries. Engagement with relevant stakeholders was not successful, and as such the estimate of bakery ovens (excluding industrial ovens) was made based on data obtained in other studies at the European level [21] and knowledge of the size of the UK bakery sector [22], [23].

From extensive engagement with the key stakeholders, it is acknowledged that detailed understanding of the commercial catering sector, particularly in terms of foodservice outlet numbers and commercial catering appliance counts, is 'locked' in the combined knowledge of a small number of consultancies and individuals with extensive experience in the industry.

Knowledge Gap: Low confidence in total installed base and relative distribution of catering appliances across the commercial subsectors and end use settings.

It is recommended to engage FEA to commission a targeted study to more accurately estimate the number of gas fired commercial catering appliances installed in commercial kitchens in the UK.

In line with the overall consumption data for catering, it is estimated that there are significantly more electric commercial catering appliances installed than gas. Feedback from the commercial catering industry suggest that electric appliances are more reliable, require less maintenance, less complicated ventilation and fewer safety interlocks. In the case of induction hobs, which are taking an increased market share (no specific figures to quantify this), significantly increased energy efficiency and safety are also achieved. For these reasons, a shift away from gas has been reported by numerous stakeholders. It is not known whether this is just a short term fluctuation or a long term change in the market.

A study [13] into energy use in commercial kitchens focussed on a number of kitchens from a chain of gastropubs. The majority of cooking appliances were electric (12) with only two gas appliances – a chargrill and a six burner range.

Feedback from CEDA is that, particularly for medium to large kitchens, the electricity supply to the building is not sufficient for all cooking appliances to be electric. To that end, kitchen designers and end users will often select one or two gas cooking appliances (usually prime cooking appliances with the highest energy demand such as ranges, grills, fryers) and the rest will be electric.

An article on FoodServiceEquipmentJournal.com [14] reveals a similar opinion from a leading UK supplier of professional cooking appliances:

> *"Electric-based solutions are becoming more and more popular as energy efficiency continues to climb the list of priorities and even though we are still approached by clients looking for a solution that balances gas and electric components, more often than not they will opt for 70%-plus electric, sometimes even 100%, once they have compared the relevant benefits,"*

This final statement about 100% electric kitchens should be read in the context of the previous discussion about power supply limitations to commercial properties. At the meeting of FEA members in March 2020, only 35% of respondents thought that full electrification of commercial catering appliances was possible.

4.5.2.5 Other Commercial Gas Appliances

The scope of the study was limited to appliances for space heating, hot water and catering. Nevertheless, some population data was obtained for the following gas appliances which contribute a significant amount to gas consumption via intensity or appliance counts.

Tumble dryers

Commercial tumble dryers are found in numerous settings, including universities, prisons, laundrettes and hospitals. The estimated installed base of gas fired commercial tumble dryers is 66,000 as determined from sales and rental data from a major UK based supplier. It was further noted that electric tumble dryers are more common in all end use settings (approximately 60% electric), and even more prevalent (70%) in university accommodation.

Cremators

Input was provided by The Cremation Society of Great Britain, who advised that there are approximately 300 crematoria in the UK with approximately 640 cremators installed, of which “the vast majority” are gas. Typically, cremators are dual-chamber (i.e. two burners) with a combined power output of 600kW and life span of 20-25 years.

4.5.3 Public Sector

Public sector end use accounts for a significant portion of commercial and industrial space heating and hot water consumption. The BEES study for BEIS in 2016 estimated consumption by public sector end users to be 32% of total non-electric consumption, of which natural gas is by far the largest contributor.

In order to gain a detailed insight into the population of gas fired appliances in the public sector, Freedom of Information (FOI) requests were sent to a range of public sector bodies – Local Authorities, NHS Trusts, Fire & Rescue Services, Police Forces, Prisons and Universities. The following data was requested:

- Appliance counts for all major heating & catering gas appliances and their respective output ratings (kW or BTU/hr);
- The footprint (m^2) and annual gas consumption (kWh) of premises owned/operated by each organisation.

4.5.3.1 FOI Response Statistics

FOI requests were sent to 598 out of 883 relevant organisations in the UK. Datasets were received from 318 of these organisations, of which 141 were deemed to be useful and usable following an initial data screening process. This screening process involved reviewing the data sets for the provision of a minimum of seven meta-data points including appliance make, model, output, age, premises footprint and annual gas consumption, amongst others.

The high-level summary figures for the FOI requests and extracted data sets for each of the relevant organisations are provided in Table 4-14.

Table 4-14 – FOI Data Request Summary

	Group						
	Fire Services	Local Authorities	NHS Trusts	Police Forces	Prisons	Universities	Total
Organisations	50	412	227	45	6	143	883
Requests Sent	33	195	207	30	6	127	598
Datasets Received	19	89	114	11	2	83 Note 1	318
Usable Datasets	11	50	65	7	2	6	141

Note 1: Most datasets were received after data collation was completed. The data could be screened and further suitable appliance records included in the overall database.

Figure 4-15 – FOI Extracted Data Coverage

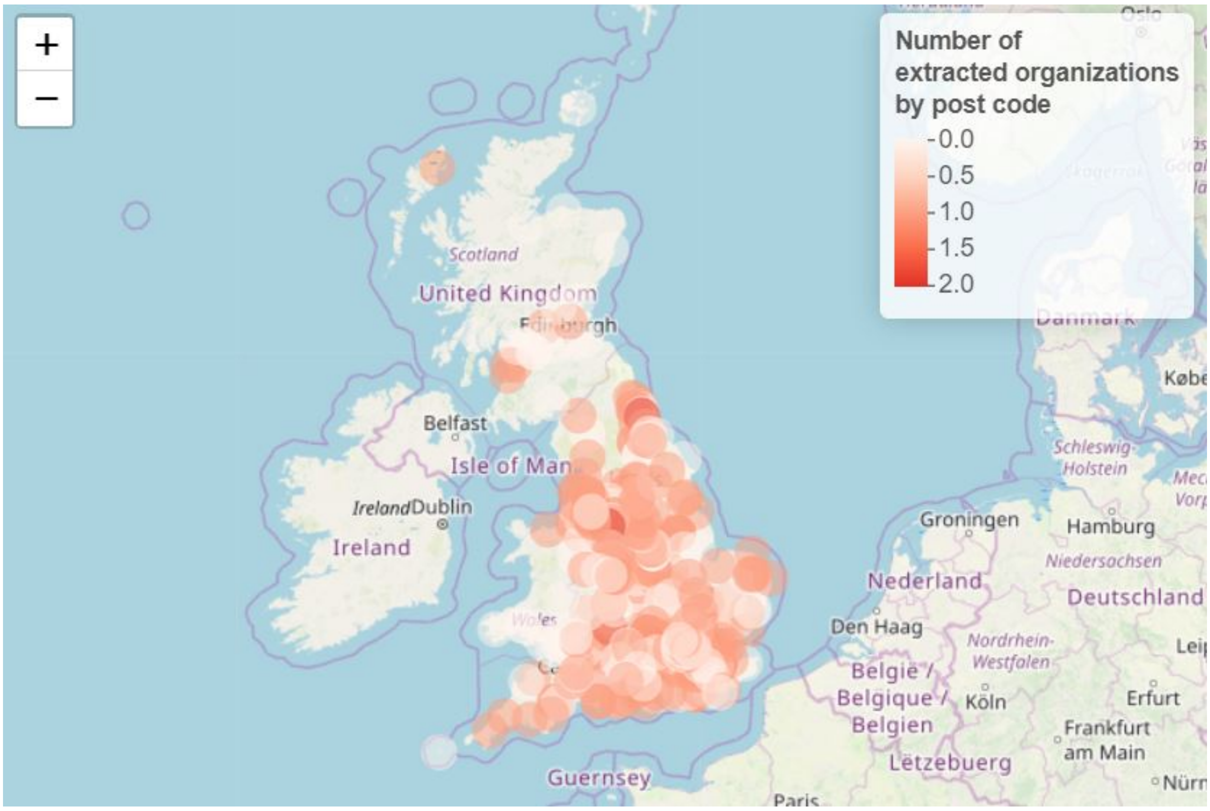


Figure 4-15 shows the geographical distribution of the data extracted from the FOI campaign. This ‘heat map’ shows that the data is reasonably well spread across the UK, with no major areas of high concentration which could potentially skew the data significantly.

Table 4-15 and Table 4-16 summarise the number of appliances extracted from the FOI data for heating and catering, respectively. More than 22,000 appliances were included in the extraction, however a significant portion of those appliances could not be used in the appliance counts below and the bottom-up estimates as some vital information was missing to allow for accurate categorisation of the appliance and/or the end use setting.

Table 4-15 – Heating Appliance Counts (FOI Data)

	Group						
	Fire Services	Local Authorities	NHS Trusts	Police Forces	Prisons	Universities	Total
Air Heater	56	612	31	22	2	16	739
Boiler (all)	598	4,244	2,013	412	124	449	7,840
Boiler (⩽30kW)	26	299	341	61	0	42	769
Boiler (>30kW)	317	1,595	957	245	29	288	3,431
Radiant Heater	80	173	19	33	0	17	322
Water Heater (direct)	68	742	209	54	2	29	1,104
Water Heater (indirect)	20	408	64	4	0	3	499
Water Heater (instantaneous)	28	112	25	0	0	0	165
Total (all boilers)	850	6,291	2,361	525	157	514	10,669

Table 4-16 – Catering Appliance Counts (FOI Data)

	Group						
	Fire Services	Local Authorities	NHS Trusts	Police Forces	Prisons	Universities	Total
Bain Marie	0	0	6	0	0	1	7
Boiling Pan	0	30	5	0	23	9	67
Bratt Pan	0	1	14	0	12	8	35
Fryer	12	120	72	3	60	31	298
Griddle	0	0	1	0	0	3	4
Grill	35	36	30	0	8	21	130
Hob	15	24	14	0	7	15	75
Oven	33	221	143	1	43	69	510
Range	31	130	77	2	17	21	278
Total	126	562	362	6	170	178	1,404

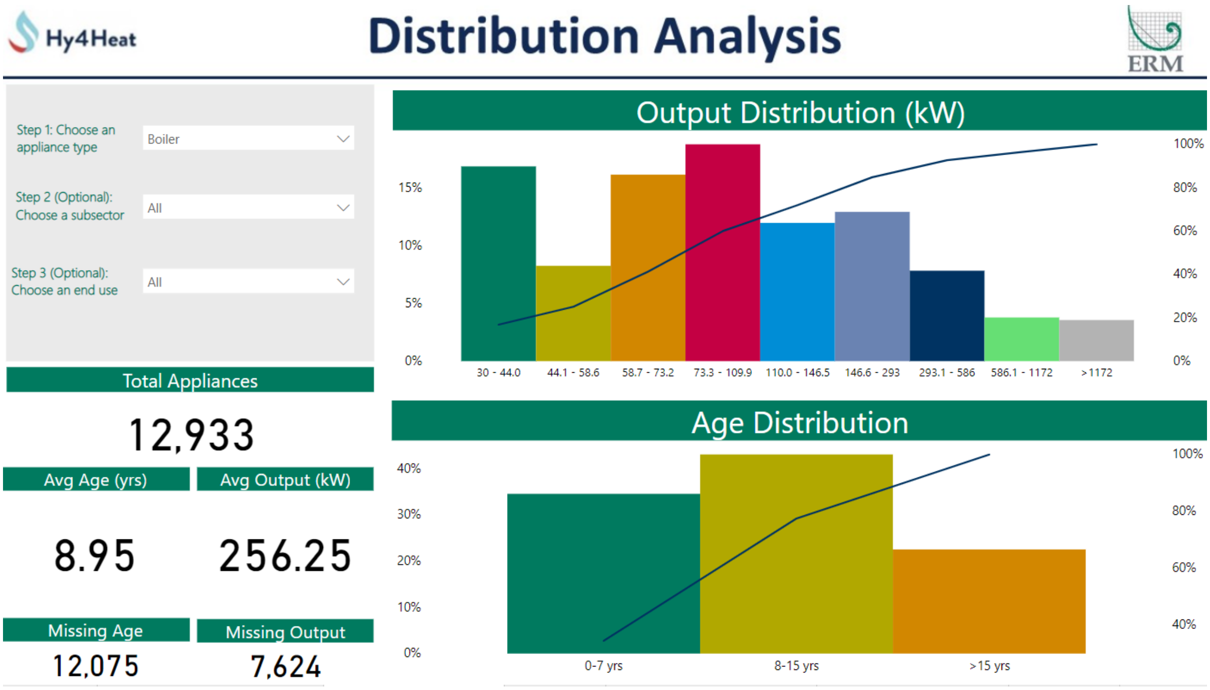
The data obtained from the FOI campaign which was deemed to be usable represents 16% of the relevant organisations; calculations completed to extrapolate the national installed base have been done so with a significant degree of uncertainty.

As described above, a significant portion of the appliances reported by responding organisations could not be accurately categorised for appliance type and/or end use setting. Therefore the bottom-up estimates for installed based are expected to be 'minimum' values.

4.5.3.2 Data Analytics

Data tools were used to analyse and visualise the appliance data obtained from the FOI campaign. As shown in Figure 4-16, dashboards can display data obtained on the number of boilers installed, the distribution of boiler outputs, and the average age and output of the boilers. This data can be shown for each appliance type and each subsector and/or end use setting. It should be noted that boilers were not only the most common appliance reported in the data, they also reported the most meta-data (e.g. output, age).

Figure 4-16 – FOI Data Analytics Dashboard



Distribution Analysis

Step 1: Choose an appliance type: Boiler

Step 2 (Optional): Choose a subsector: All

Step 3 (Optional): Choose an end use: All

Total Appliances: 12,933

Avg Age (yrs): 8.95

Avg Output (kW): 256.25

Missing Age: 12,075

Missing Output: 7,624

Source: ERM Power BI Dashboard

Boilers were by far the most common heating and hot water appliance reported in the FOI data, contributing nearly 60% of the appliances reported in the extracted data. The extracted data also showed that approximately 14% of boilers (590 of the 4,200 with recorded output ratings) used in commercial settings are domestic sized appliances (<30kW).

Wet / Dry Split of Heating Appliances

The extracted FOI data provides an insight into the split of wet versus dry heating in the relevant subsectors. This is summarised in

Table 4-17 and used as an input to the top-down estimate of heating appliances based on natural gas consumption data.

Table 4-17 – Wet / Dry Split of Heating Appliances (Extracted FOI Data)

Subsector	% Dry Heating Appliances (i.e. Warm Air and Radiant Heaters)
Fire Services	19%
Local Authorities	18%
NHS Trusts	2%
Police Forces	12%
Prisons	2%
Universities	7%
Total	**13%**

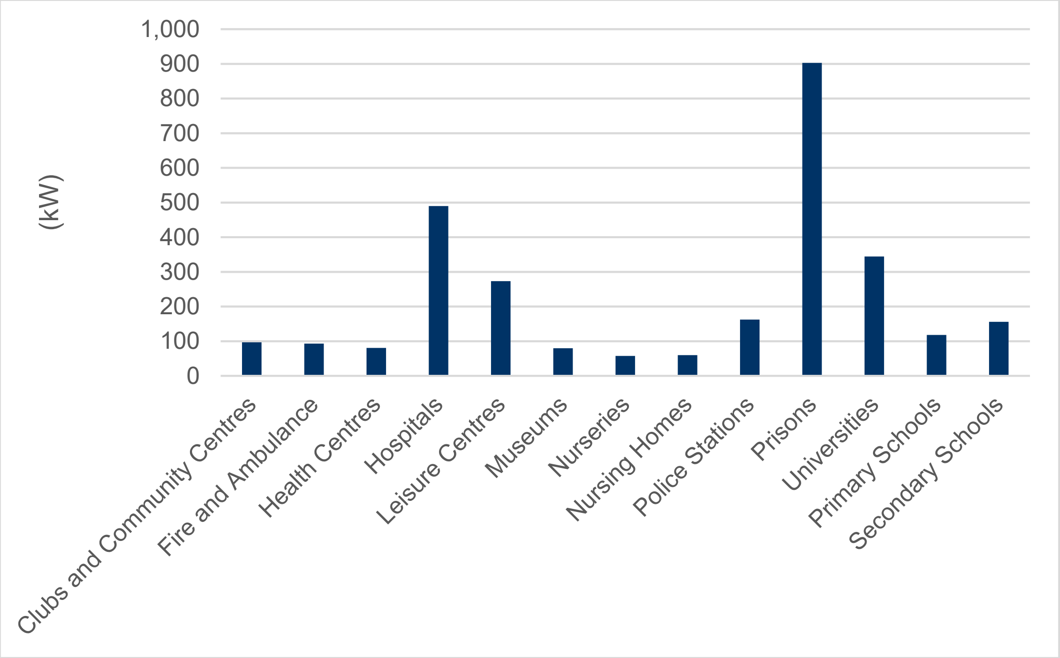
It is noted that the splits shown in

Table 4-17 are based on appliance number and not output or consumption.

Heating Appliance Outputs

The data obtained from the FOI responses was used to determine the average boiler size for the key subsectors and end use settings. Graphical distributions of boiler outputs are provided in Appendix A and summarised in Figure 4-17 below.

Figure 4-17 - Average Boiler Output by End Use (FOI Data)



The data shows that Prisons and Hospitals use heavy commercial/industrial boilers more than other end users in the public sector. This is reflective of the size of the sites and round the clock heating demands. Hospitals recorded 13% of boilers with rated outputs of 400kW or greater (137 of 1050) and Prisons more than 45% (16 of 35). The Education sector also reports a significant number, 49, almost equally split across Primary and Secondary schools; however this represents only a small fraction of the overall population of 941 (5.2%) across the two end uses.

Overall, a total of 409 boilers with rated output of 400kW or greater were recorded out of 4,200 units reported with their output (9.7%). ICOM sales data suggests the contribution of units with output of 400kW or greater is less than 5%.

Other end use settings with large average boiler sizes are Leisure Centres and Universities, both of which often have swimming pools heated by boilers, increasing the overall site heating demand.

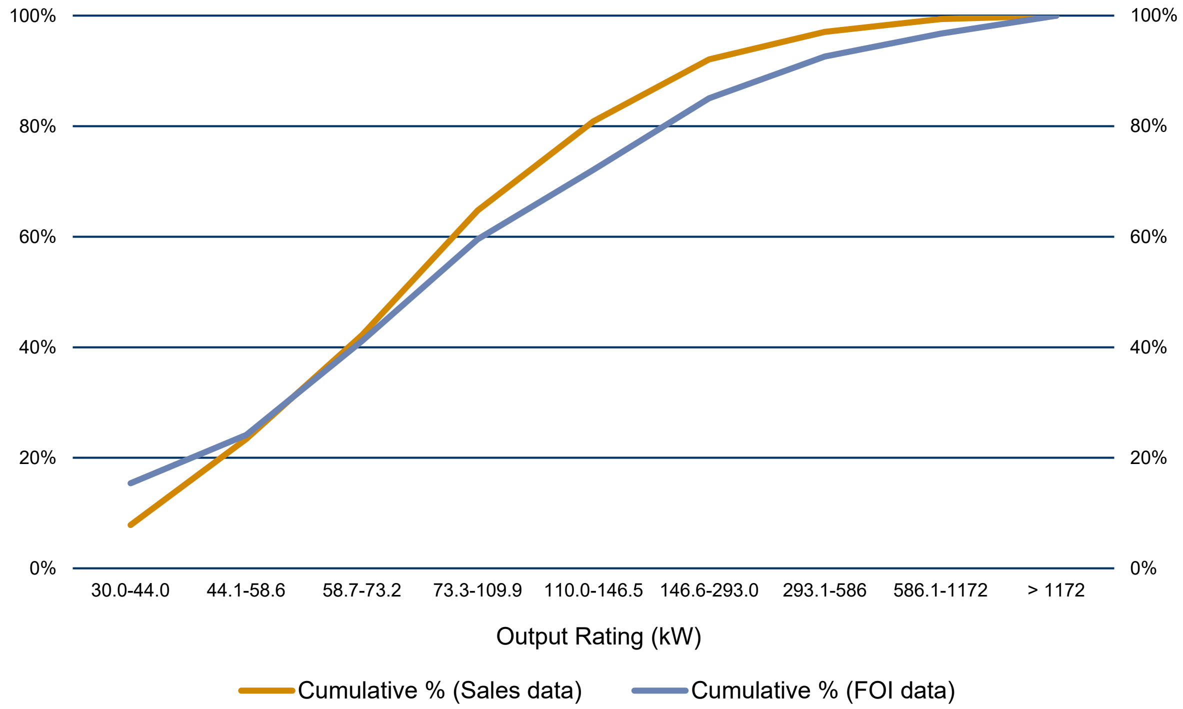
By contrast, Nursing Homes use boilers at the low end of the commercial spectrum on average, reflective of the domestic-like setting and usage patterns.

The distribution of boiler outputs in the data obtained from FOI responses was compared to the sales data for a recent 12 month period provided by ICOM. The cumulative frequencies show a significant shift from larger units to smaller units, most notably for output category 110-146.5kW and greater. FOI data suggests that the 24% of boilers are greater than 146.5kW and 6.4% greater than 586.1kW, which is comparable with recent ICOM sales data that suggests these figures are less than 20% and 5%, respectively.

Figure 4-18 aligns with the feedback from manufacturers that more units are being sold as part of cascade systems (estimated 70% of unit sales), which has the effect of reducing the average size of installed boilers, shifting the distribution curve to the left towards smaller units.

Furthermore, it is suggested that by the time transition to 100% hydrogen might occur, in the order of 10 years, the distribution of installed boilers will be closest to that of the recent ICOM sales data as old boilers are increasingly retired/replaced with newer smaller units.

Figure 4-18 – Cumulative Distribution of Boiler Outputs – Sales versus FOI Data

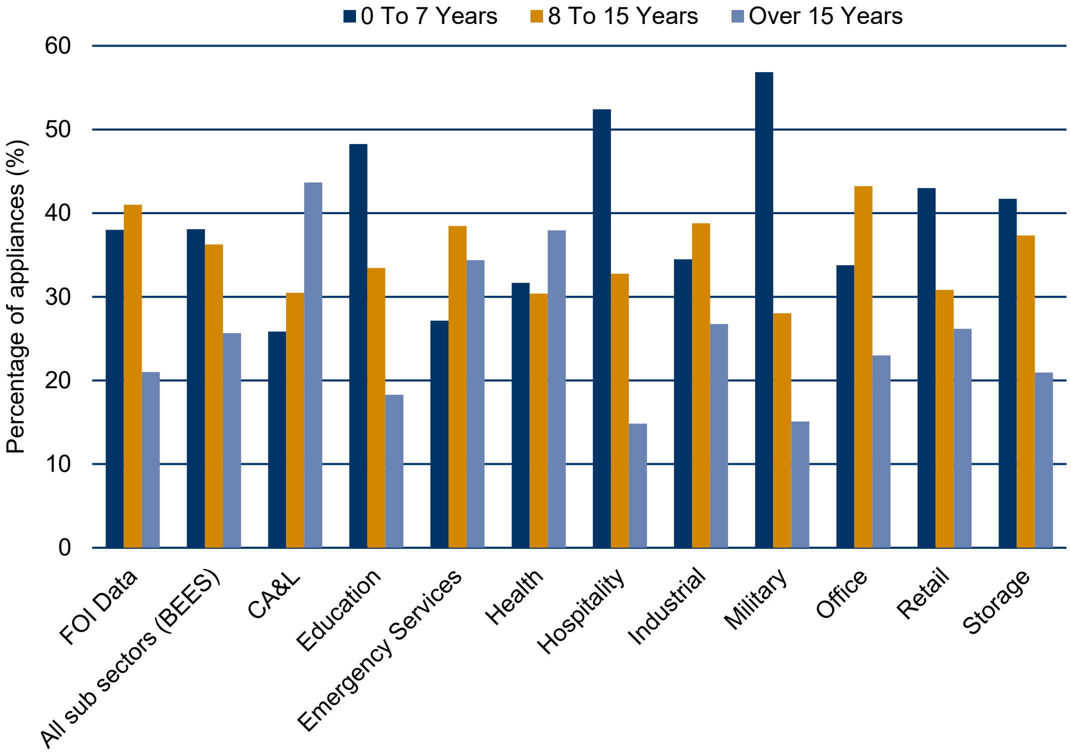


Appliance Age Distribution

The BEES study completed for BEIS in 2016 provided an insight into the age of boilers installed in the Commercial and Industrial sectors. Data obtained from FOI requests shows a very similar profile for the overall population. Note that the category “Don’t Know” in the BEES data has been apportioned over the three age brackets, and the same for appliances in the FOI data where an age was not provided.

There appears to be a very minor shift to younger appliances, as evidenced by the reduction in appliances over 15 years (21% in the FOI data versus 26% in the BEES data). This could be seen as further evidence of the increase in popularity of cascade units, with older larger units being replaced by new smaller units. However, the data sets are only 4 years apart, and the impact of this change is not likely to be quite so marked, and is therefore not considered to be statistically significant.

Figure 4-19 – Boiler Age Distribution – FOI Data versus BEES Data



Indicative Distributions by Subsector/End Use Setting (Bottom-up Estimate)

The relative distribution of boilers within the commercial subsectors and end use settings is not in the public domain. The data obtained from the FOI responses has been used to generate a bottom-up estimate of the number of boilers within those public sector end use settings where sufficient data was available.

It is important to note that the bottom-up figures are indicative only due to the potential errors through the data gathering and extraction process. This includes potential errors with inputs from responding organisations, missing appliance information and erroneous classification of end user premises types. Various quality control reviews were conducted on the extracted data, however it is noted that due to the volume of and variation within the data, some errors may still exist.

Full details of the bottom up calculations, including numbers of appliances in the FOI data, number of responding organisations and/or premises, and the actual number of relevant organisations/premises in the UK for extrapolation are provided in Appendix C. A summary of the bottom-up estimates is provided in Table 4-18 for end use settings with sufficient data.

Table 4-18 – Estimated Number of Commercial Boilers (Public Sector, Bottom-up)

End Use	Estimated Number of Boilers in UK
Clubs and Community Centres	39,002
Fire and Ambulance	5,936
Hospitals	7,349
Leisure Centres	13,476
Nurseries	14,462
Police Stations	3,042
Prisons	1,081
Universities	10,124
Primary Schools	44,883
Secondary Schools	42,243

The Education subsector is by far the largest market for commercial boilers by unit volume within the public sector. Hospitals and Prisons were noted earlier as having on average the largest boilers, and this is similarly reflected in the fact that they represent a relatively small fraction of the overall population of installed boilers (i.e. small number of large boilers to meet the required heating demand).

Catering Appliances

Appliance data obtained from the FOIs may provide some useful insights into public sector kitchens, however it is should be noted that food service in these end use settings is often outsourced to Facilities Management (FM) companies, and therefore kitchen appliance data may not be accurate. The relative prevalence of appliances reported in the FOI data is similar to that proposed by manufacturers, however ovens are the highest reported appliance whereas ranges are thought to be more common. This may be a result of the different designs in public sector kitchens versus private kitchens, or it may be down to misclassification of ranges as ovens.

No valid conclusions can be drawn from the FOI data for catering appliances as it currently stands.

4.5.4 Private Sector End Users

There is a large data gap for appliances installed in private sector end use settings – these organisations are not bound by FOI laws and have proven much less willing to provide information. Numerous attempts to obtain data on private sector appliances were made, including direct contact with large end users, via trade bodies and appliance distributors, however no meaningful data was obtained.

A small data set was provided by one Facilities Management company, with appliance counts for several private sector end use settings including offices and manufacturing facilities. However, at the time of writing this report the data did not include key meta-data such as output rating, age or any details on the setting (e.g. footprint) and was therefore not included in the analysis.

Most organisations were eager to learn more about the potential for hydrogen to decarbonise heat in the UK, but quickly disengaged on the basis that it was not a viable option for implementation in order to meet their sustainability goals within the next 2-3 years.

Knowledge Gap: Commercial appliance counts and distributions within private sector end uses.

It is recommended that further engagement with FM companies is attempted to obtain detailed appliance data for private sector users.

5. TECHNICAL CHALLENGES OF CONVERSION TO HYDROGEN

5.1 Latest Knowledge

A review of literature for the current state of the market for commercial appliances revealed that there has been limited development of commercial appliances to run on 100% hydrogen. Previous studies for BEIS [15] and DECC [16] touch on some of the commercial appliances presented in this report, and provide extensive discussions of the technical challenges involved in converting them to run on hydrogen.

From these studies and further review of publicly available data, it is clear that appliance development has been focussed on domestic and industrial sized appliances. Until recently, developments had largely been 'hobbyist', or niche developments, including those utilising low temperature catalytic combustion. However, the potential for a hydrogen economy has encouraged significant developments involving domestic appliances.

Work Package 4 (WP4) for the Hy4Heat project is currently developing a wall-hung condensing boiler fuelled by hydrogen. No details are available on the specific design, and no results on performance have been shared to date, however the basic technology in use is expected to be directly relevant to a 'light' commercial boiler in the range 30-70kW. According to ICOM sales data, this would cover more than 40% of commercial boiler sales.

Another significant trial taking place at the time of preparing this report is the Power2Gas project [17] in Rozenburg, Netherlands. Three boilers fuelled by 100% hydrogen were installed in a 'boiler house' connected to an apartment complex. The boilers were fed with (nominally) 100% hydrogen produced locally. Again, no results for the performance of the boilers are available in the public domain yet.

5.2 Appliance Technical Barriers to Conversion

This section provides a discussion of the level of barrier the technical challenges present (including technology readiness). The results of surveys, round tables and site visits are incorporated. Generally, the summary technical position on conversion of natural gas to hydrogen is that with sufficient effort, nationwide conversion is technically feasible. Underpinning this summary position is that production of hydrogen is possible via various processes (e.g. electrolysis, steam reforming etc.), hydrogen will burn with a stable flame profile to release thermal energy which can be used by suitable heat exchangers and suitable hydrogen/ air burners for appliances are in development. One of the main benefits of the use of hydrogen is removal of CO_x from the combustion products, specifically carbon dioxide (CO_2) which is a contributor to climate change and carbon monoxide (CO) which is the main cause of natural gas gas-based fatalities observed within the UK.

However, although technically possible and with many benefits, some significant challenges exist between the ideal of technical feasibility and production of a safe, commercially viable hydrogen network. Some of these challenges include (but are not limited to):

a) hydrogen has significantly different physical and chemical properties compared to natural gas and these will potentially affect safe working practises including ATEX zoning of gas facilities, safety distances between network pipelines and buildings / structures.

b) hydrogen burns with a higher flame velocity that may affect rate of pressurisation in situations where gas accumulation has occurred prior to ignition (e.g. during delayed ignition)

c) material embrittlement by hydrogen for metallic components may be marked for hydrogen pipework compared to natural gas (generally where metallic components are under physical loading)

d) appliances set for optimum performance with natural gas would be predicted to either fail in function or reduce markedly in efficiency with hydrogen so would require "retrofitting" of suitable subcomponents to allow function on hydrogen.

e) the Wobbe number is similar for both hydrogen and natural gas and so should have similar power delivery through network pipework. However, some minor changes to operating pressures and combustion air supply may be required to achieve equality with energy delivery of natural gas.

In essence, all of the above (and mostly all technical challenges) are considered to be manageable if sufficient financial resource is available. However, the financial requirement to achieve suitable level of control may prove prohibitive. Consideration of the economic effects of conversion have not been applied to the discussion below except where specifically referenced as an area that underpins a technical barrier.

5.2.1 Formal Stakeholder Responses

5.2.1.1 Appliance Design Considerations

Heating and catering appliance manufacturers were asked within a survey to choose the three design goals they believed to be the hardest to achieve for a new appliance operating on 100% hydrogen. These were to be rated from 1 (hardest to achieve) to 3 (easiest to achieve) and the answers were weighted as such.

The choices given were; achieving functional goals, achieving aesthetic quality, achieving efficiency goals, achieving safety goals, achieving emissions standards, development of an economically viable and competitive product, or “other” (manufacturers were given the opportunity to provide alternative design goals).

The same question was raised at a round-table discussion with the ICOM Boiler & Hot Water manufacturer members, to noticeably different responses. It should be pointed out that the sample size for the manufacturer’s survey (2) was far smaller than the round table (16), and as such the results should be treated with due caution.

Figure 5-1 – Appliance Design Considerations – Heating Appliances (Manufacturer Survey)

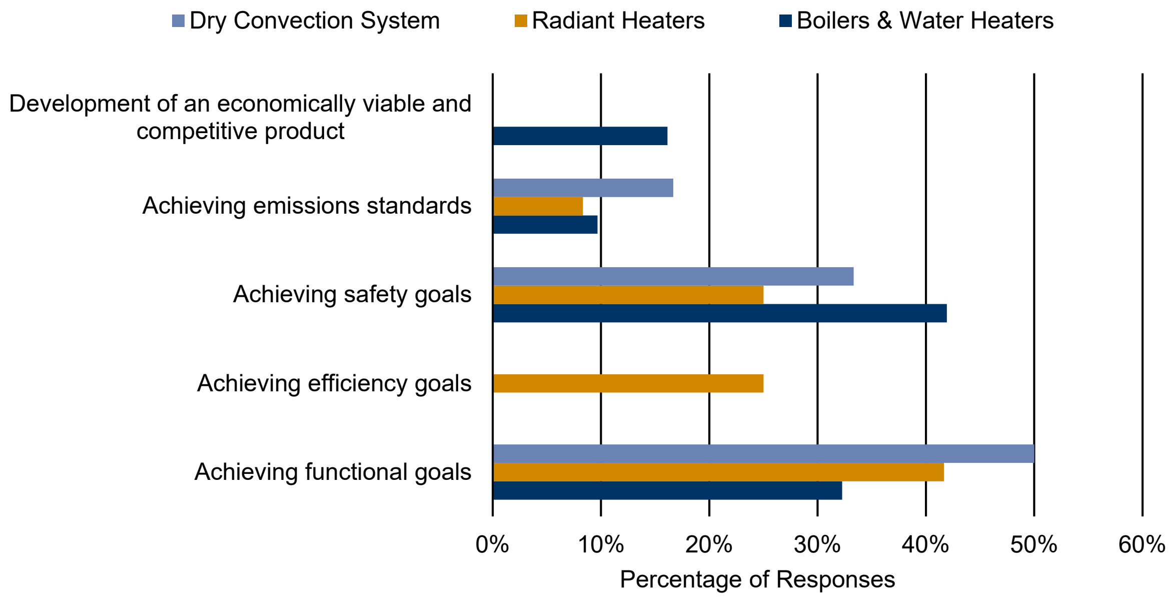


Figure 5-2 – Appliance Design Considerations – Catering Appliances (Manufacturer Survey)

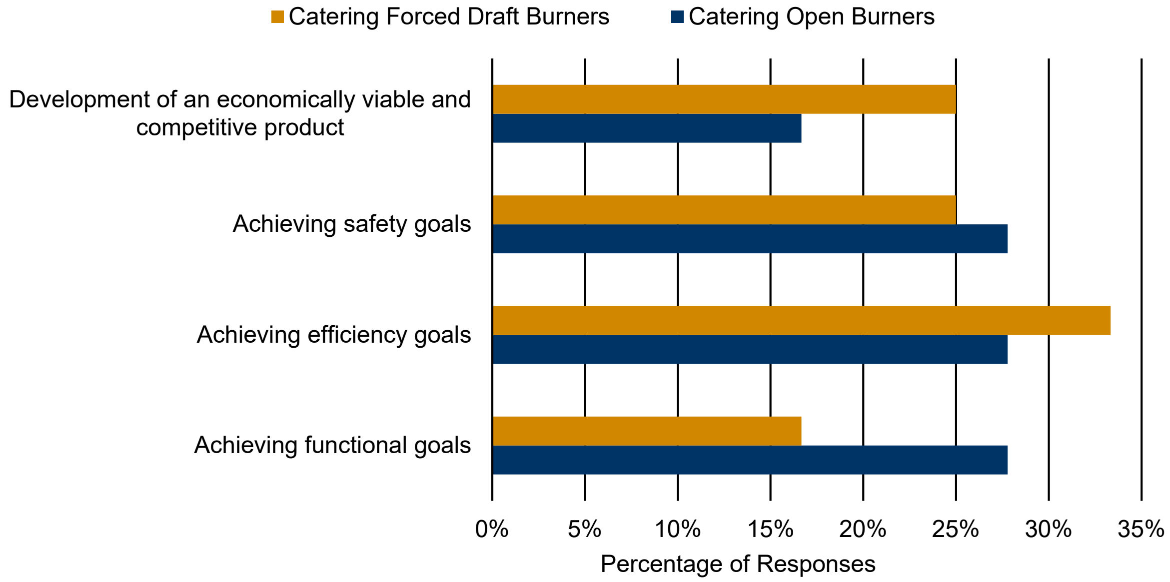
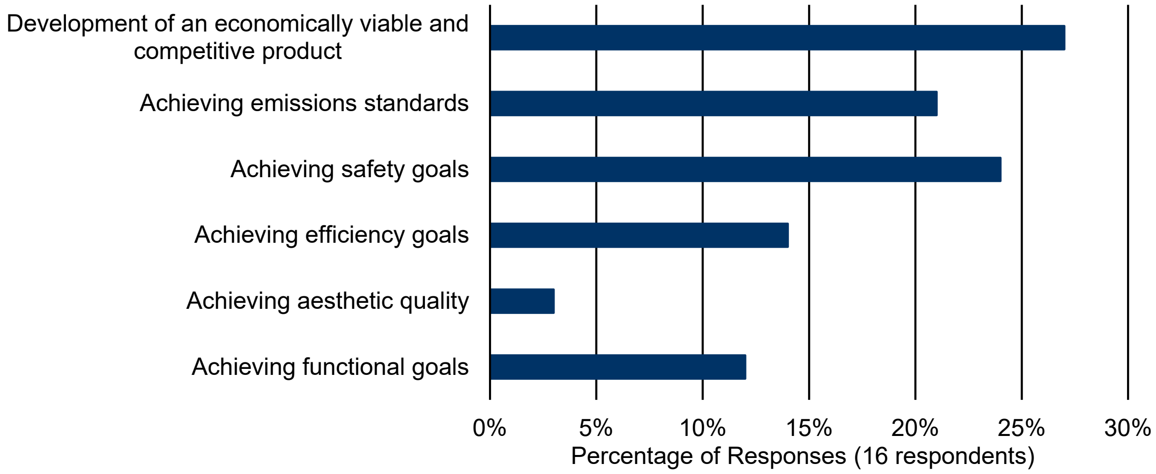


Figure 5-3 - Appliance Design Considerations – Boilers and Water Heaters (ICOM Round Table)



The round table survey shows that manufacturers are primarily concerned with development of an economically viable and competitive product, achieving safety goals and achieving emissions targets, in that order. The economics of new hydrogen appliances is indelibly linked to the level of difficulty in achieving the other stated goals, and is discussed further in Section 7.

Achieving safety goals and emissions standards for boilers and hot water heaters are a function of the component level challenges and are discussed in detail in Section 5.2.1.2.

5.2.1.2 Component Level Challenges

Component level challenges were developed in consultation with HSE Science Division and based on the process flow diagram presented in Figure 5-4. The full list of challenges is provided in Table 10-1 along with a detailed description of the level of difficulty to overcome.

Manufacturers were asked to select the top five component level challenges, ranking them from 1 to 5 (where ‘1’ is the greatest concern). The responses provided by the manufacturers are summarised in Figure 5-5 and Figure 5-6. Note, only those challenges for which a response was provided are shown in the graphs (i.e. other challenges did not receive any votes from the responses received).

It must be noted that the number of respondents was eight – consisting of five heating appliance manufacturers and three catering appliance manufacturers. Further feedback on technical challenges was received through one-to-one conversations and is summarised in Section 5.3.

Figure 5-4 - Commercial Appliance Technical Challenges – Process Flow Diagram

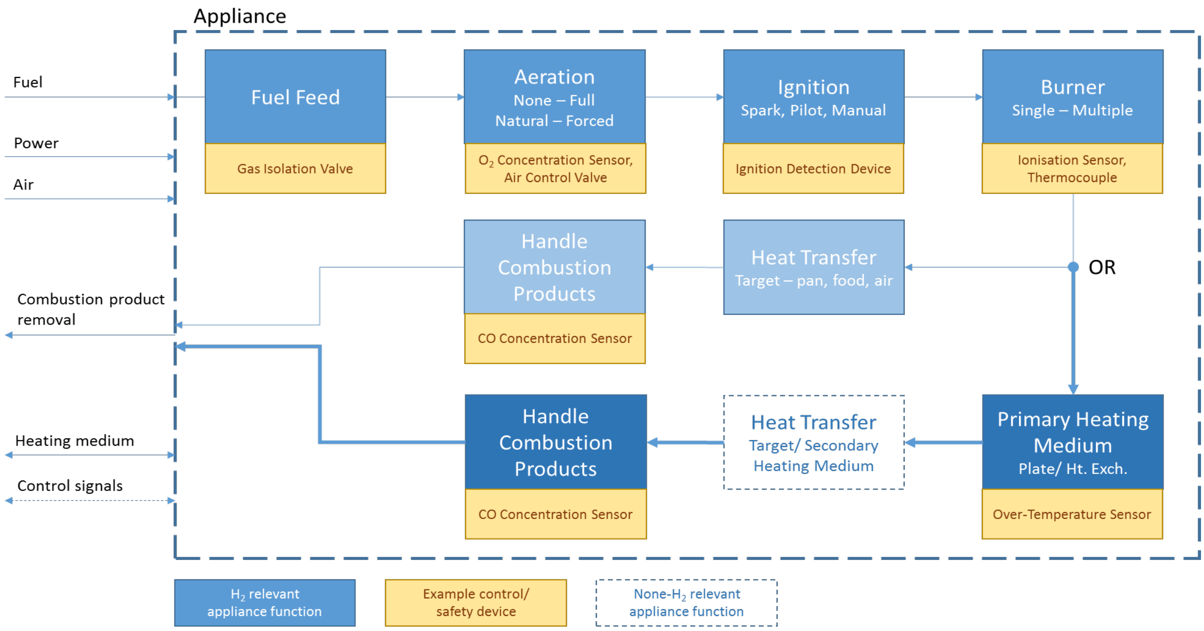


Figure 5-5 - Component Technical Challenges – Heating Appliances (Manufacturer Survey)

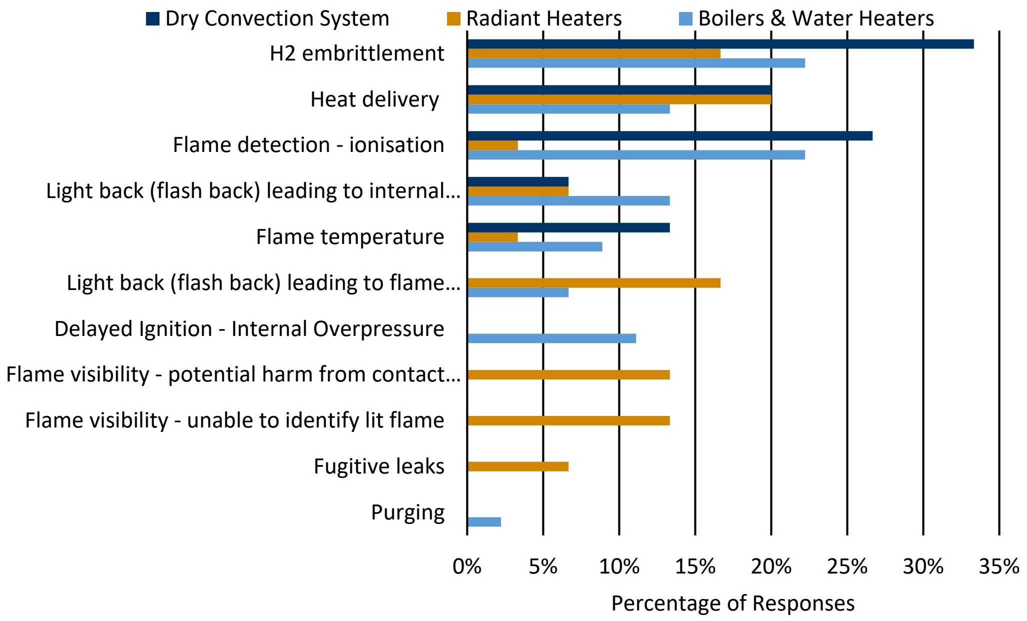


Figure 5-6 - Appliance Design Considerations – Catering Appliances (Manufacturer Survey)

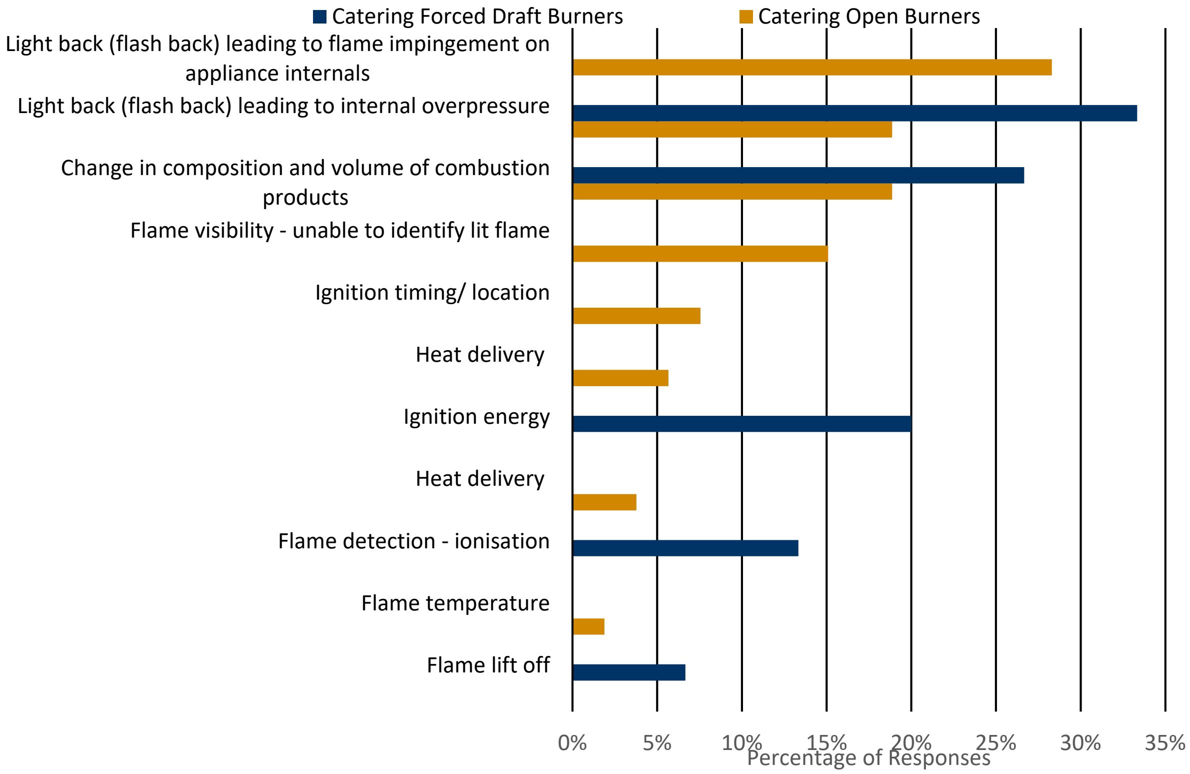
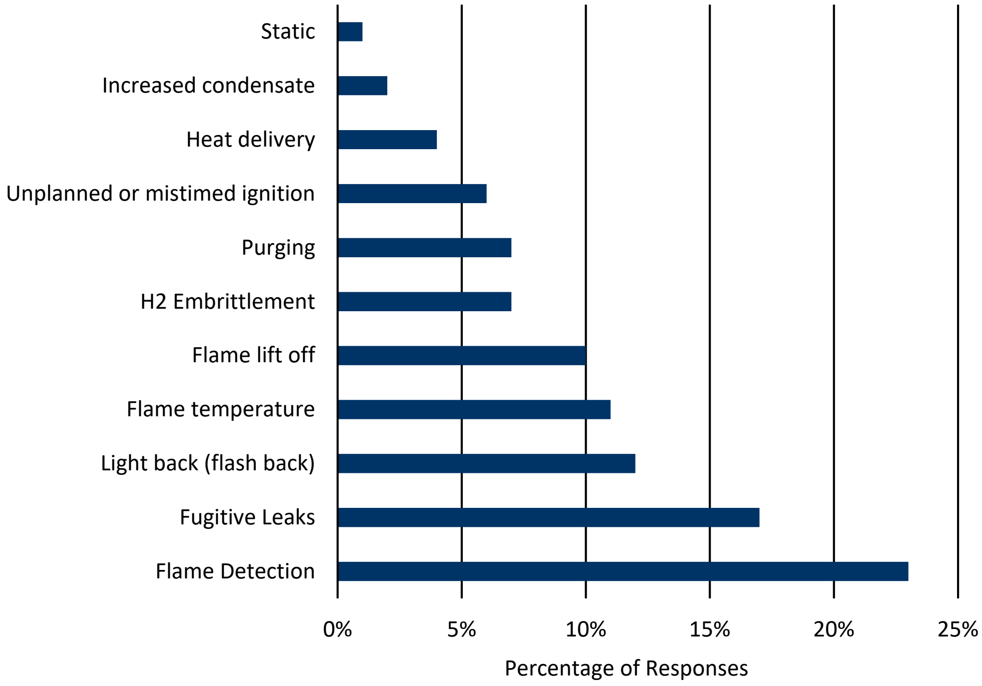


Figure 5-7 - Component Technical Challenges – Heating Appliances (ICOM Round Table)



It is clear that there are a range of component level concerns for commercial appliance manufacturers. The appliance manufacturers generally do not have direct experience of working with 100% hydrogen, which has led to a wide variety of challenges being selected as the most critical across the two surveys.

It is recommended that a knowledge sharing event is held for appliance manufacturers to understand the current research programs and knowledge base for working with 100% hydrogen to facilitate further appliance development.

A detailed technical review of the component level technical challenges, their significance and measures to overcome is provided in Appendix D.

5.3 Technical Challenges – Discussion

This section provides further discussion of some of the key technical challenges raised as part of the stakeholder engagement process for this study.

As stated within Section 5.2, the pure technical challenges associated with producing hydrogen, burning it at a suitable burner surface and then transferring the heat produced to a heat exchanger all appear achievable if sufficient resource and review is undertaken.

Wider technical barriers focus strongly on control of hazards in accident situations where hydrogen is correctly perceived to be of significantly different hazard to natural gas. The main differences are the wider flammable limit, the lower minimum ignition energy and the higher laminar flame speed of any flame: in combination these lead to a material that ignites more easily, over a wider range of concentrations to produce a faster flame front. This flame front releases energy more rapidly into the local environment producing a higher over-pressure over a shorter period, potentially leading to wider damage to structures and the public.

To minimise the effects of these consequences of accidental release, a wider program of education and demonstration of operator competence may be required aligned to wider education of the general public on the pros and cons of hydrogen usage.

Achieving safety goals, consistently highlighted by appliance manufacturers as one of the main challenges, should largely be addressed by the work already underway as part of the other Hy4Heat work packages.

The development of PAS4444 in WP3 for the certification of hydrogen fuelled domestic appliances is also intended to cover commercial appliances. The PAS will cover functional specification of appliances including specific advice on demonstration of safety, specifically for defined ‘extreme events’ where safety systems are assumed to have failed. This demonstration of safety will address some of the key technical challenges raised by manufacturers including light back, flame lift-off and delayed or unintended ignition (in the appliance case and flue). PAS4444 will also define the requisite limit gases to be used for appliance safety testing.

Domestic appliance development within WP4 will address many of the key safety challenges identified for commercial appliances in this study and covered by PAS4444. The unique safety challenges posed by commercial appliances which are not equally relevant to domestic appliances are:

- Commercial ovens are often not supplied with automatic ignition devices, requiring instead to be lit manually with the doors open. This is unique to the commercial sector. Guidance for safe ignition of commercial ovens while minimising the risk of generating a flammable atmosphere outside the oven cavity should be considered within the development of PAS4444.
- Commercial boilers can be significantly larger than domestic boilers (i.e. up to 1 MW versus average 20kW). The additional volume of the appliance, and the elevated flowrate of hydrogen fuel feed, provides an increased risk of potentially damaging overpressures in the event of delayed ignition. The development of PAS4444 should take this into consideration,

and potential mitigation measures should be explored during appliance development as part of WP5b.

Additionally, the appliance setting and relevant safety standards should be reviewed for applicability with 100% hydrogen. Key areas for review include:

- Safety valve ratings and maximum permissible leak rates. Hydrogen is a smaller molecule than natural gas, and the increased potential for leakage of hydrogen past the safety valve must be reviewed to determine new maximum permissible leak rates.
- DSEAR impacts. Significant changes to hazardous area ranges and equipment temperature classification as a result of change from natural gas to 100% hydrogen should be defined. Increased leak potential from vibration induced fatigue was highlighted as a potential concern for large commercial appliances.
- Ventilation requirements. Minimum ventilation rates within building regulations should be reviewed to identify any changes required to accommodate 100% hydrogen as fuel.
- Flue arrangements. It has been noted by several manufacturers that current flues may not be suitable for 100% hydrogen due to increased water vapour content in flue gas. Also, there may be factors which prevent hydrogen/hydrogen-ready boilers being installed in the same flue system as natural gas boilers. Guidelines for flues should be reviewed for applicability to 100% hydrogen as fuel, accounting for the period of transition from natural gas to hydrogen appliances.
- Commercial kitchen guidelines. Functional requirements for ventilation interlocks should be reviewed for applicability with 100% hydrogen.

Functionally there are further technical barriers which must be overcome to develop commercial appliances which meet the same level of performance as existing natural gas appliances. Heat exchange in the various appliances is likely to be impacted by the changed flame profile of 100% hydrogen combustion. Hydrogen flames generate almost no radiant heat, which is normally responsible for a significant amount of the overall heat exchange of a three-pass shell and tube heat exchanger within the combustion chamber.

The potential for flame impingement on the heat exchanger (or any other internal item which would not normally be exposed directly to flame) and any impacts to heat exchange should be carefully studied.

The ability to meet the same, or at least very similar, output in the same footprint as existing natural gas appliances will be vital for many commercial appliances. Boiler rooms, plant rooms and commercial kitchens can be very cramped spaces, and therefore any increase in appliance footprint should be avoided to minimise potential impacts on other appliances.

Emissions and efficiency targets are critical for heating appliances up to 400 kW. Given that 100% hydrogen burns with a higher flame temperature than natural at stoichiometric conditions, it is considered theoretically likely that NO_x emissions will be higher per kW heat output . Feedback from industry is that warm air heaters are already having difficulty meeting the next round of ErP targets (2016/2281 from 1st January 2021) for NO_x emissions and efficiency concurrently.

It is recommended that a warm air heater is developed as part of WP5b to determine the impact of burning 100% hydrogen on meeting the 2021 ErP targets.

The key functional test for commercial catering appliances is a taste test to determine the quality of the cooked product. The presence of additional water vapour in the combustion products may impact the way in which food cooks, altering taste, texture or flavour. Secondary to this is the cooking time required using a hydrogen flame. Any significant increase to cooking times should be avoided to minimise impacts to commercial kitchen schedules and cooking capacity.

As part of the demonstration trials, consider implementing a taste test for foods cooked using hydrogen appliances versus natural gas and electric.

5.4 Implications for Appliance Development

As shown in Appendix D, generally all appliances will require a design review to ensure that changes to fuel gas type do not impact too severely onto function, safety, emissions and efficiency. It is expected to be likely that a high degree of “read-across” from one design standard to another would be possible (e.g. in how burner design is affected by hydrogen) but further work would certainly be required to demonstrate this safe working prior to use of a modified natural gas-based appliance design for hydrogen gas feed.

Burners and associated flame supervision devices have been identified as the key components for development of hydrogen appliances by the majority of stakeholders. While it has been noted that successful trials have been completed by burner manufacturers and other domestic appliance development trials (e.g. Hy4Heat WP4, Rozenburg), commercial appliances use a wide variety of burners to achieve their functional requirements. Development of a suitably varied mix of burners compatible with 100% hydrogen for use in commercial boilers, water heaters, warm air heaters, radiant heaters and commercial catering appliances is vital to proving the technical feasibility of converting the commercial sector to hydrogen.

One burner manufacturer has reported successful trials with 100% hydrogen using a pressure jet burner in the commercial appliance range (approximately 50-150kW). The trials, although limited, revealed no technical ‘show stoppers’ to safe combustion using 100% hydrogen. Stable flames were produced, and with the standard flame rectification probe substituted for a UV detection device, successful flame monitoring was achieved. Initial results revealed that per kW energy input compared to natural gas there is an increase in water vapour content in the flue gas (approximately 50%). It also revealed an increase in the temperature within the heat exchanger due to the increased flame temperature using 100% hydrogen, which on its own would likely lead to increased NO_x generation, but could be mitigated by design optimisation.

Each of the major technical challenges raised by manufacturers have, in principle, design options available which could be incorporated to overcome the potential barrier.

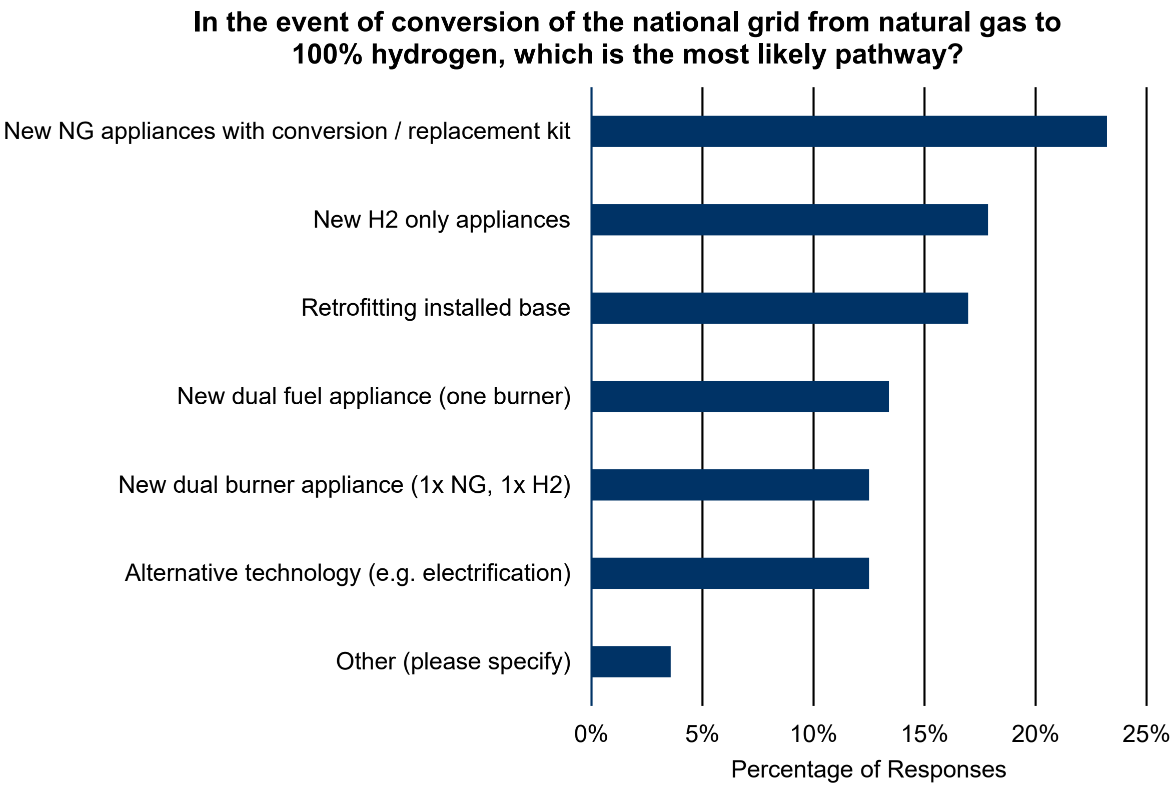
- Flame detection. Current methods used for detecting natural gas flames (ionisation probe, thermocouple) may not be suitable for 100% hydrogen. Alternative technologies (e.g. UV detection) are already available and proven.
- Light back. The laminar burning velocity of hydrogen, and the presence of a flammable mixture within pre-mix burners, give rise to the risk of light back, with the potential for major damage to boiler components. Careful design of burners to enhance ‘quenching’, and operating with excess air for combustion are potential options for mitigating the risk. For larger burners, flame arrestors could be used to protect the gas supply train.
- Increased flame temperature and NO_x emissions. Hydrogen burns at a higher temperature than methane at stoichiometric conditions, introducing the risk of damage to internal components, and increasing the generation of NO_x in the flue gas. A variety of means for reducing NO_x emissions are available, including flue gas recirculation (for large appliances, >500 kW) or excess combustion air to cool the flame.
- Material compatibility and lifetime testing. Hydrogen is known to cause embrittlement in some materials, and since the H_2 molecule is smaller and more diffusive than natural gas, the risk of leaks leading to accumulation and unwanted ignition/explosions is increased. A program of work to test all ‘wetted’ parts is required to identify suitable materials to mitigate this risk.

Heat exchangers will also be key, with the interaction between the burner and heat exchanger making a significant contribution to meeting emissions and efficiency targets. Hydrogen burns with different radiation/convection characteristics to natural gas. Optimisation of the efficiency of a new/redesigned heat exchanger will be required.

Finally, to roll-out a program of change to a pure hydrogen-based fuel gas will require a transition period where the network ran on pure natural gas to one of pure hydrogen. For appliances designed for use with natural gas, consideration of how this transition would be achieved in the interim period where natural gas based appliances will potentially not function correctly with a pure hydrogen gas feed. Possible routes could be by the use of “dual fuel” or “hydrogen ready” appliances with retrofitting of modified injectors etc. but it seems unlikely that switch over would occur for the whole of the UK in a short time period and so these “stepping stone” methods might not mitigate against delays / appliance malfunction.

Figure 5-8 shows the relative contributions that each appliance conversion mechanism will make in the event of conversion of the Commercial sector from natural gas to 100% hydrogen for boilers and water heaters. The development of new natural gas appliances which can function on natural gas and can be readily converted to function on 100% hydrogen is considered to be the most likely option to facilitate the transition which is expected to occur over a period of more than 20 years (see Section 7.1.4.3).

Figure 5-8 – Commercial Sector Conversion and Appliance Development Options – Manufacturer’s Views (Boilers and Hot Water)



5.4.1 Emissions and Efficiency

Emissions and efficiency targets are critical for heating appliances up to 400 kW. One of the key technical challenges for conversion of the commercial sector to hydrogen is achieving the current limits for NO_x emissions. The ecodesign regulations impose limits on the allowable amount of NO_x emissions from relevant gas fired appliances. A summary of the current limits for appliances which are covered in WP5 is provided in Table 5-1.

Table 5-1 – Current NO_x Emissions Limits for Commercial Appliances

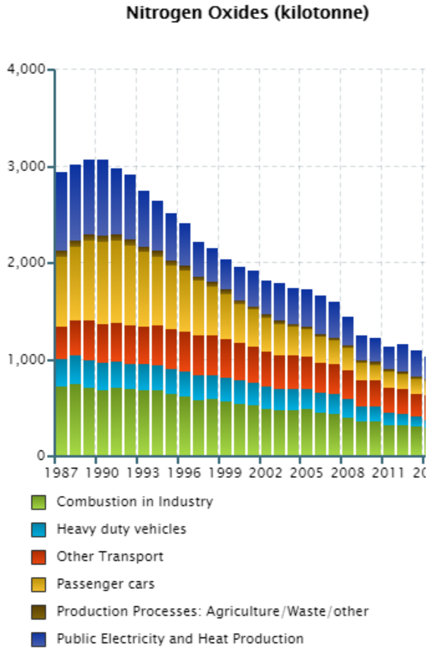
Application	Appliance	Current NO_x limit (mg/kWh input)	Relevant Regulation / Standard
Space Heating	Boiler (⩽ 400 kW)	56	813/2013
	Boiler (400 – 1,000 kW)	170	EN 303-7
	Warm Air Heater	100	2016/2281
	Radiant Heater	200	2015/1188
Hot Water	Water Heater	56	813/2013
Catering	Catering Appliances	N/A	N/A

In the UK as a whole the principal sources of NO_x emissions are:

- Industrial combustion
- Heavy duty vehicles
- Other transport (shipping, rail, commercial vehicles etc.)
- Passenger cars
- Production processes (i.e. agriculture, waste management etc.)
- Public electricity and heat production

In urban areas, NO_x concentrations have generally been decreasing in line with national strategies and policies to reduce emissions. Figure 5-9 shows UK NO_x emissions and how these have varied between 1987 and 2013.

Figure 5-9 – UK NO_x Emissions by Source (1987 – 2013) (Source: NAEI[6])



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[6] National Atmospheric Emissions Inventory (accessed July 2019) About Nitrogen Oxides http://naei.beis.gov.uk/overview/pollutants?pollutant_id=6

Within the urban environment where there are the large majority of issues with NO_x, commercial sources make up a small overall proportion of NO_x emissions. Given that 100% hydrogen burns with a higher flame temperature than natural gas at stoichiometric conditions, it is considered theoretically possible that NO_x emissions will be higher per kW heat output. Feedback from industry is that natural gas warm air heaters are already having difficulty meeting the next round of ErP targets (2016/2281 from 1st January 2021) for NO_x emissions and efficiency concurrently. However, manufacturers working on Hy4Heat domestic appliances have preliminary findings that NO_x emissions were lower than natural gas equivalents, while maintaining efficiency. Further evidence is required on commercial scale air heaters to indicate whether well-designed appliances could meet emissions and efficiency limits. Hy4Heat WP5B has funded commercial scale air heater development which will address this evidence gap.

Any potential increase in NO_x emissions in the commercial sector as a result of converting to hydrogen would have very little effect on overall NO_x emissions. This is important for the transition to hydrogen, where the overall net increase in NO_x within the commercial sector is likely to be in the order of a few percent.

However, of note is that changing combustion technology to hydrogen will renew the combustion fleet more rapidly than would have otherwise been achieved, and older higher emission equipment will be removed sooner. To some extent this could offset the marginal increase in NO_x emissions due to burning hydrogen rather than natural gas; indeed, it may be that this change will entirely offset and lead to net zero change in NO_x emissions. In the event that manufacturers can develop hydrogen appliances which achieve lower NO_x emissions than the current natural gas appliances, the positive effect of removing heavy emitting equipment will be felt even more acutely.

More critically, the provision of a hydrogen network offers the opportunity for greater uptake of zero-NO_x emission vehicles in urban areas. Given the proportion of NO_x that arises from vehicles in the most polluted locations, even relatively small numbers of petrol and diesel vehicles transitioning to zero-NO_x hydrogen technology could provide important gains.

Efficiency targets for commercial appliances are also set by the ecodesign regulations and relevant standards. For appliances with no specific target, the principle of rational use of energy as defined in the Gas Appliances Regulation (GAR) applies: “Appliances shall be so designed and constructed as to ensure rational use of energy, reflecting the state of the art and taking into account safety aspects.”

5.5 Knowledge Gaps

The fundamental physics and chemistry related to hydrogen gas combustion and safe use are generally well understood and documented in the public domain. However, how this fundamental knowledge impacts on commercial appliance design, safety and performance will require significant further study from individual appliance manufacturers to fill knowledge gaps.

Knowledge Gaps: appliance longevity; heat transfer effects due to changes in flame profile (potential flame impingement, lack of radiant heat); possible changes to flame monitoring and control systems; impacts to appliance footprint to meet same outputs as natural gas equivalent appliance; ability to meet emissions and efficiency targets concurrently; which appliances could be economically converted and which could not; and specific flueing requirements.

6. WIDER CHALLENGES OF CONVERSION TO HYDROGEN

6.1 Market/ Economic

This section provides insight into the challenges provided by the market and economics of commercial appliance development in the UK. Most of the quotes in this section were provided by manufacturers during a WP5 supplier's event hosted by Hy4Heat and BEIS in May, 2019.

> *"Investment is difficult if there is uncertainty about the eventual market."*
>
> *"Heating appliances are too bureaucratic, need government support"*

The H21 LCG report [18] describes the market push and retrospective market pull effects required to enable a hydrogen economy. A recent paper [19] on the decarbonisation of heat in the UK notes similar, suggesting that "'green gas' [hydrogen produced with renewable energy sources] involves the wrong sort of technology and the wrong sort of economics", and that a hydrogen economy "could only be delivered on the basis of a major strategic decision by the Government and a clear vision of the future low-carbon energy system".

Commercial end users cannot plan for hydrogen yet as it is too far off and not guaranteed to be part of the energy mix. Those end users looking to reduce their carbon footprints as part of improved operational sustainability are already making (and enacting) plans to use alternative low carbon sources. This may have the effect of reducing the size of the commercial heating appliances market available for manufacturers to provide hydrogen appliances for by the time they are commercially available.

> *"This market is not as consumer driven as WP4."*
>
> *"There is no commercial argument for manufacturers to develop commercial boilers."*
>
> *"Any involvement now is simply to be seen doing the right thing."*

The above feedback highlights why development of commercial appliances to run on 100% hydrogen has not commenced. The commercial appliance market is very different to the domestic appliance market, most notably in size. According to figures from BSRIA [20], domestic boiler sales in the UK are in the order of 1.6 million units per year whereas ICOM reports commercial boiler sales of 28,000 units per year. On its own, the UK commercial appliance market is not large enough for all of the current boiler manufacturers to switch production to hydrogen/hydrogen ready boilers and maintain profitability. The annual sales figures for other commercial appliances are lower still.

The small market for Commercial appliance sales in the UK provides an even larger challenge for manufacturers to make a return on their investment in the event of a staged conversion over a number of years. In such a scenario, end users may hold out purchasing a new appliance for longer than normal if transition to 100% hydrogen is scheduled to occur in the near future. As a result, sales might fall to the minimum required to facilitate conversion of the current area undergoing transition. The potential financial impact of this has not been studied in any detail, and should be discussed further with manufacturers as more details of the conversion pathway and hydrogen appliance development costs become available.

There is a feeling that the Commercial appliances sector lags behind both Domestic and Industrial in terms of appliance development. The Domestic market is enormous, and therefore even a small share of that market equates to a large volume of units for potential sales. At the other end of the scale, Industrial appliances are the largest fuel users, and therefore priority targets for efficiency improvements and decarbonisation developments such as the Industrial Fuel Switching competition.

> *"In the UK, there will be no R&D capacity for a boiler that is limited to a hydrogen market."*

While there are some exceptions, most UK commercial appliance manufacturers belong to multinational corporate entities with R&D carried out by centralised group facilities located in Europe. Budgets for R&D are largely committed up to 2 or 3 years in advance, and priority is normally given to programs which could deliver the biggest return on investment in the shortest time. It has been noted that UK commercial appliance manufacturers are therefore more like 'assemblers'.

> *"Testing requires a large cost of H_2 alone"*

Boiler manufacturers have indicated that it normally takes 3 – 5 years to bring a new product to market. Contributing to this is lifetime testing, or accelerated life testing, where components are tested in the lab for their ability to withstand many cycles (typically up to 10,000), and appliance performance testing, often completed in the field over two winters.

At an assumed cost of £70 per 1.5 m^3 bottle of hydrogen (assuming that no local hydrogen production is available), and eight bottles per hour for a 100kW boiler, fuel costs for testing would come to £560 per hour. Over the testing period described above, this is a significant cost for manufacturers to incur for fuel for just one appliance, with most manufacturers producing a number of appliances with multiple variants for output rating.

It is recommended that investment in hydrogen production facilities is prioritised to be able to support hydrogen appliance testing with cost effective fuel.

Currently manufacturers produce a large number of appliances with multiple variants for output rating. The trends towards cascading smaller units promotes manufacturing efficiency by reducing the number of different components required, and increasing the volume of those being produced, to deliver increased economy of scale. Potential synergies with domestic appliance development taking place in WP4 should be explored (see below).

6.2 Industry / Supply Chain

This section discusses the challenges provided by industry and the supply chain for Commercial appliances.

> *"Collaboration with common supply chain, especially for components e.g. burner contact assembly"*

There is a relatively small pool of component manufacturers supplying commercial appliance manufacturers in the UK. In particular there are far fewer burner manufacturers than appliance manufacturers, with many burner manufacturers supplying their products across the full spectrum of commercial heating appliances. Cylindrical metal fibre burners, for example, are one of the most commonly used burners in commercial appliances, with outputs ranging from 1 to 3,000kW and can be used in boilers, water heaters, warm air and radiant heaters, and catering appliances.

It has been suggested that the commercial appliance manufacturers should look to the automotive industry as an example of manufacturers coming together for research and development in the transition away from fossil fuels.

> *"Exploitation of the benefits of H_2 as per WP4. Make the appliance better, more stable flame."*

It should be noted that there was limited engagement with burner manufacturers in this study despite attempts to contact. Similarly, there was limited sharing of information from WP4 due to the restricted nature of the intellectual property being developed. Commercial appliance manufacturers would benefit from controlled sharing of information with those who have already started development with technology that is largely shared between the Domestic and Commercial sectors.

In order to promote appliance development, it is recommended that knowledge sharing events are held with appliance manufacturers, component manufacturers (especially burners) and independent design houses. The objective for this would be to discuss the current state of

research and development and promote efficiency in the development of a suite of hydrogen appliances.

A lack of testing facilities has been highlighted as a potential bottleneck for appliance development. A shortage of trained competent Gas Safe engineers for working with 100% hydrogen, both short term for appliance development and testing, and long term for grid conversion and appliance installation, has also been highlighted as a potential cause of delay to development and conversion.

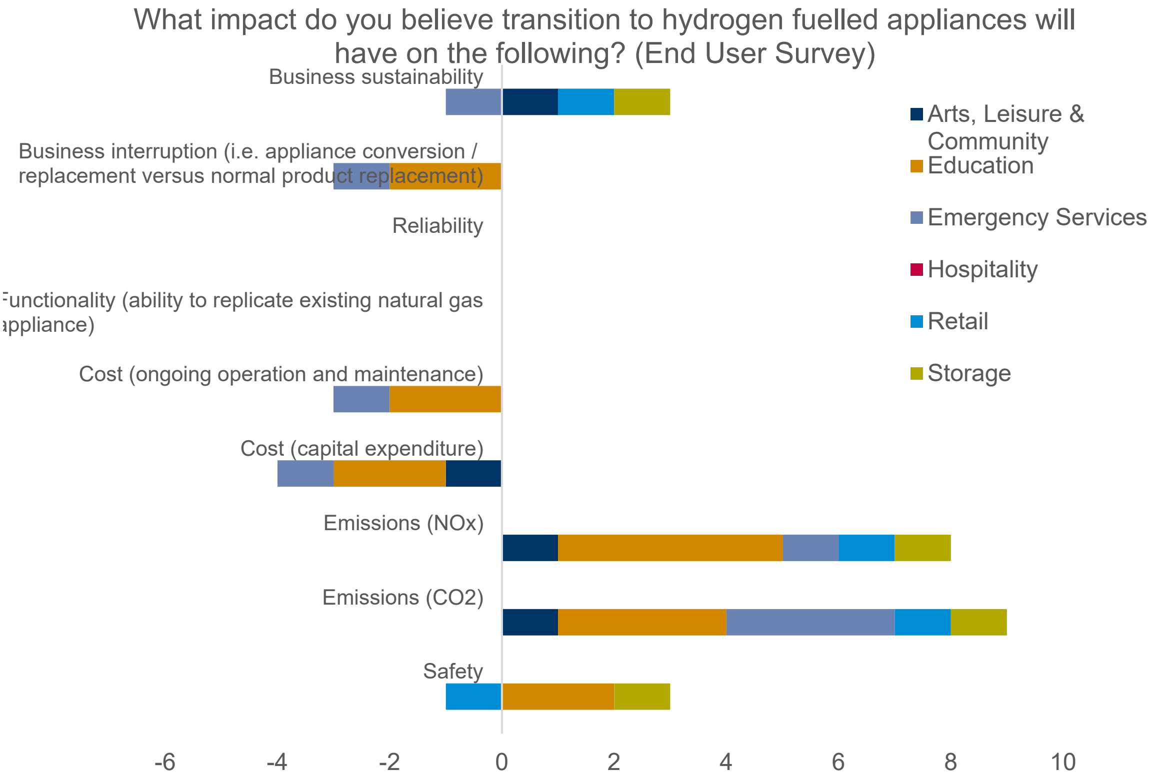
6.3 Securing User Acceptability

When considering end users in the commercial sector, these may be the final consumers of hydrogen, or they may be any one of a number of procurement and facilities management roles who ultimately decide which heating technology to procure/install. This decision can be based on a variety of factors, and these factors will be of differing importance between the sub-sectors and end uses within the commercial sector.

Awareness of hydrogen as a potential low carbon fuel for heating is moderate, with 33% of respondents to a survey of commercial end users admitting that they were unaware of this. Furthermore, the average of the respondents' self-rated knowledge of the potential for hydrogen to reduce carbon emissions was slightly 'below average' at 2.75 (based on a '1' to '5' rating system).

Survey respondents were asked to identify whether transition to hydrogen would have a positive, negative or no impact on a variety of issues. From a mix of end users and facilities management respondents across various Commercial end uses, the survey responses identified net positive impacts for the following:

- CO_2 emissions (i.e. reduction)
- NO_x emissions (i.e. reduction)
- Business sustainability
- Safety.



The fact that safety was predicted to be improved by switching from natural gas to hydrogen was unexpected. Informal discussions with other commercial end users highlighted safety as a potential concern, with some end users referring to hydrogen as being ‘more explosive’. However, one end user went on to say that if transition to hydrogen was to occur, then it was their belief that it could only happen if the Government was satisfied that there was no additional risk to the public, and therefore they would accept hydrogen as a safe and viable alternative fuel for heating.

Very few end users correctly identified the absence of carbon monoxide (CO) in hydrogen combustion products as a potential safety benefit during informal discussions. CO poisoning is the largest cause of fatalities in the UK related to natural gas usage, approximately eight times more lethal than fires caused by natural gas appliances.

It is recommended that a campaign of public information sessions is held, including commercial end users, to promote the potential benefits of transitioning heating to hydrogen and share current knowledge on the safety aspects of replacing natural gas with hydrogen.

Business interruption was highlighted as a problem by both end users in the survey and manufacturers in the WP5 supplier’s event.

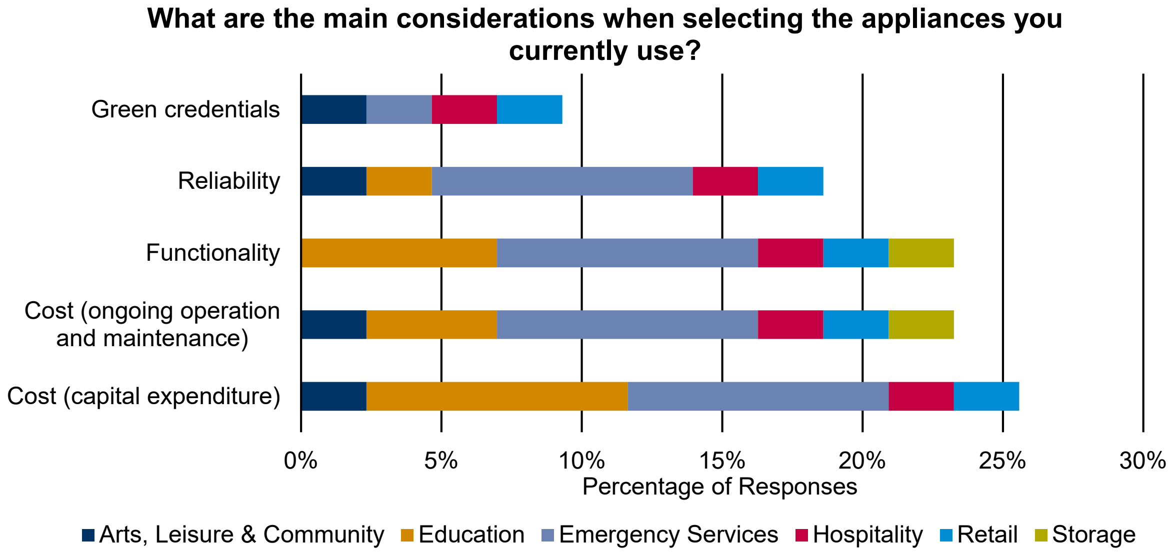
> *“Business interruption and compensation [is a concern].”*

Commercial end users are very different to domestic end users. The vast majority of commercial end users are private sector, existing to generate a profit, while the remaining end users are public sector, providing services to the community. Many end users operate 24 hours per day, 7 days per week, providing critical care and support. Any major interruption to or loss of heating could lead to significant impacts on their operations, with potential financial or care quality implications.

The process for converting commercial end users must be considerate of the unique demands for heat within each end use type, as well as any other conversion constraints such as geography.

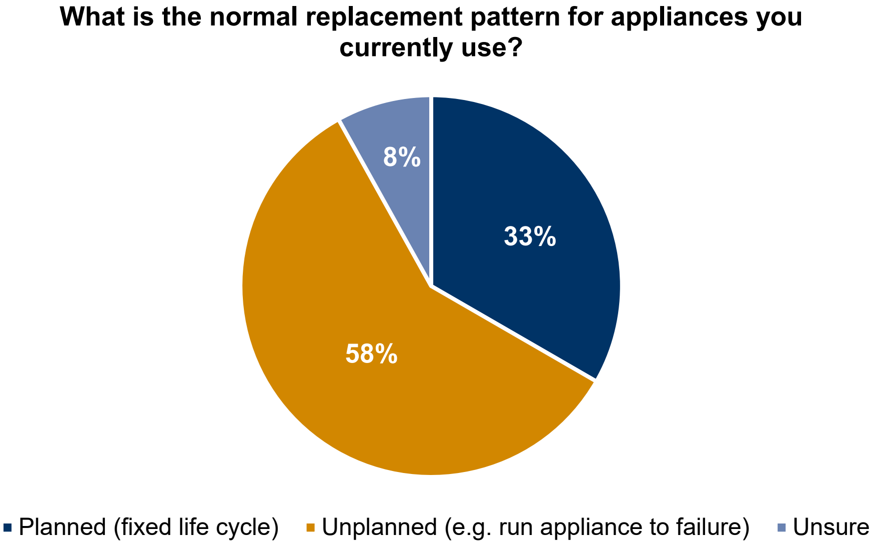
The results for end users’ main considerations when selecting new appliances indicate that cost and functionality are the most important factors. It was interesting to note that green credentials was their least important consideration from the list of options provided. This suggests that until hydrogen compatible appliances are available at a competitive price and with equivalent or better functionality, then there will not be widespread demand for them.

Figure 6-1 - End User Survey, Appliance Considerations Reposnses



Commercial end users were also asked to identify which factor drives appliance replacement, to which the majority responded that they run appliances to failure before replacing them. As some appliances have a life expectancy of 25 years or more, this could affect potential conversion as end users may be unwilling to replace appliances which still meet their functional needs.

Figure 6-2 - End User Survey, Appliance Replacement Pattern Responses



6.3.1 Commercial Catering Appliances

End users of commercial catering appliances currently have the choice of gas or electric for all appliance types. The choice between the two fuels is often a function of a number of factors, including current fuel supply to the building, purchase cost, fuel cost, willingness to install additional ventilation and safety interlocks for gas appliances, and chef's preference, which is a function of cooking technique and quality/taste of the cooked food. In the event of a transition to hydrogen, the same factors would still apply, however one major unknown is the quality/taste of food cooked using hydrogen.

Knowledge Gap: Bake quality and taste of bread products baked in appliances using 100% hydrogen is unknown.

It is recommended that engagement with stakeholders in the Bakery sector is made, and that as part of the appliance demonstration trials, a variety of bread products are baked and subjected to taste tests to highlight any major differences with natural gas baked products.

7. COST AND TIMELINES FOR CONVERSION

In this section of the report ERM's analysis of the cost and timeline for R&D, testing and conversion/replacement of the selected commercial appliance types is summarised.

The key objectives of the analysis were:

- Estimate the costs to research, develop and test each of the selected commercial appliance types, based on feedback from manufacturers, publicly available research and ERM's analysis.
- Estimate the costs to convert or replace all units of that type of appliance which are currently installed in the UK.
- Estimate the high-level timeline for both the research/development/testing phase, and the conversion/replacement phase. The timeline is highly dependent on policy signals, however consideration of this is beyond the scope of ERM's analysis, as is detailed consideration of practical methodologies for conversion of the UK (for example phased geographic rollout), therefore the analysis of timing is relatively high level at this stage and focussed on feedback from manufacturers and publicly available research on what is technically feasible given the current TRL of the appliances.

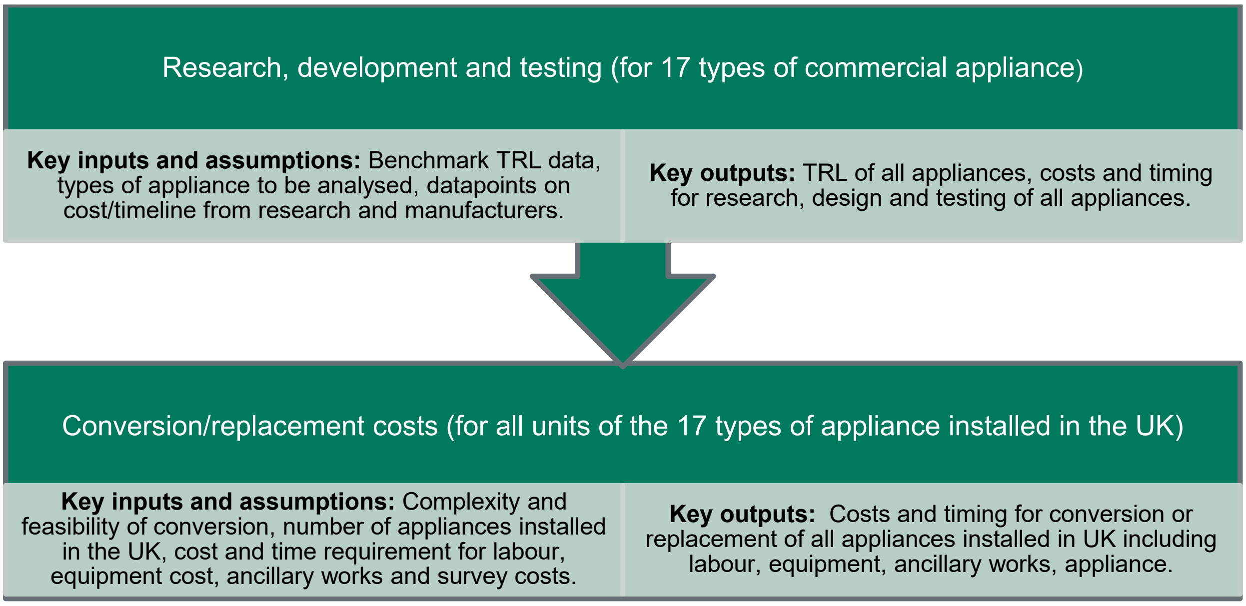
Note that for clarity the following terminology has been used throughout this section:

- "Replacement" refers to the replacement of an entire appliance, in other words the appliance is removed and replaced with an appliance which can run on 100% hydrogen.
- "Hydrogen ready" appliances could run on both natural gas and hydrogen and/or be designed to involve very low conversion costs to run on hydrogen rather than natural gas.
- "Conversion" refers to the change-out of required components in order to convert an existing appliance running on natural gas so that it can run on 100% hydrogen.
- "Light" conversion costs are those associated with converting a hydrogen ready appliance, while "Heavy" conversion costs are those associated with converting a natural gas only appliance which is not hydrogen ready.

ERM's analysis has focussed on the "conversion" and "replacement" of appliances which may fall into one of three categories:

- Appliances which need to be "replaced" because it is technically/economically unfeasible to convert to run on hydrogen.
- "Hydrogen ready" appliances which require only "Light" conversion costs in order to be able to run on hydrogen.
- Non-hydrogen ready appliances, which require "Heavy" conversion costs in order to be able to run on hydrogen.

The scope of this analysis covers the costs and timeline associated with conversion/replacement of the three categories above, in addition to research, development and testing costs, as shown in Figure 7-1 below.



Research, development and testing (for 17 types of commercial appliance)

Key inputs and assumptions: Benchmark TRL data, types of appliance to be analysed, datapoints on cost/timeline from research and manufacturers.

Key outputs: TRL of all appliances, costs and timing for research, design and testing of all appliances.

Conversion/replacement costs (for all units of the 17 types of appliance installed in the UK)

Key inputs and assumptions: Complexity and feasibility of conversion, number of appliances installed in the UK, cost and time requirement for labour, equipment cost, ancillary works and survey costs.

Key outputs: Costs and timing for conversion or replacement of all appliances installed in UK including labour, equipment, ancillary works, appliance.

Figure 7-1 - Scope of Cost and Timeline Analysis

The key methodologies, inputs, assumptions and results of these elements are discussed in turn in the following sections.

7.1 Appliance Analysis

7.1.1 Appliance Definition

Seventeen types of commercial appliance were considered as part of the analysis, as presented below in Table 7-1.

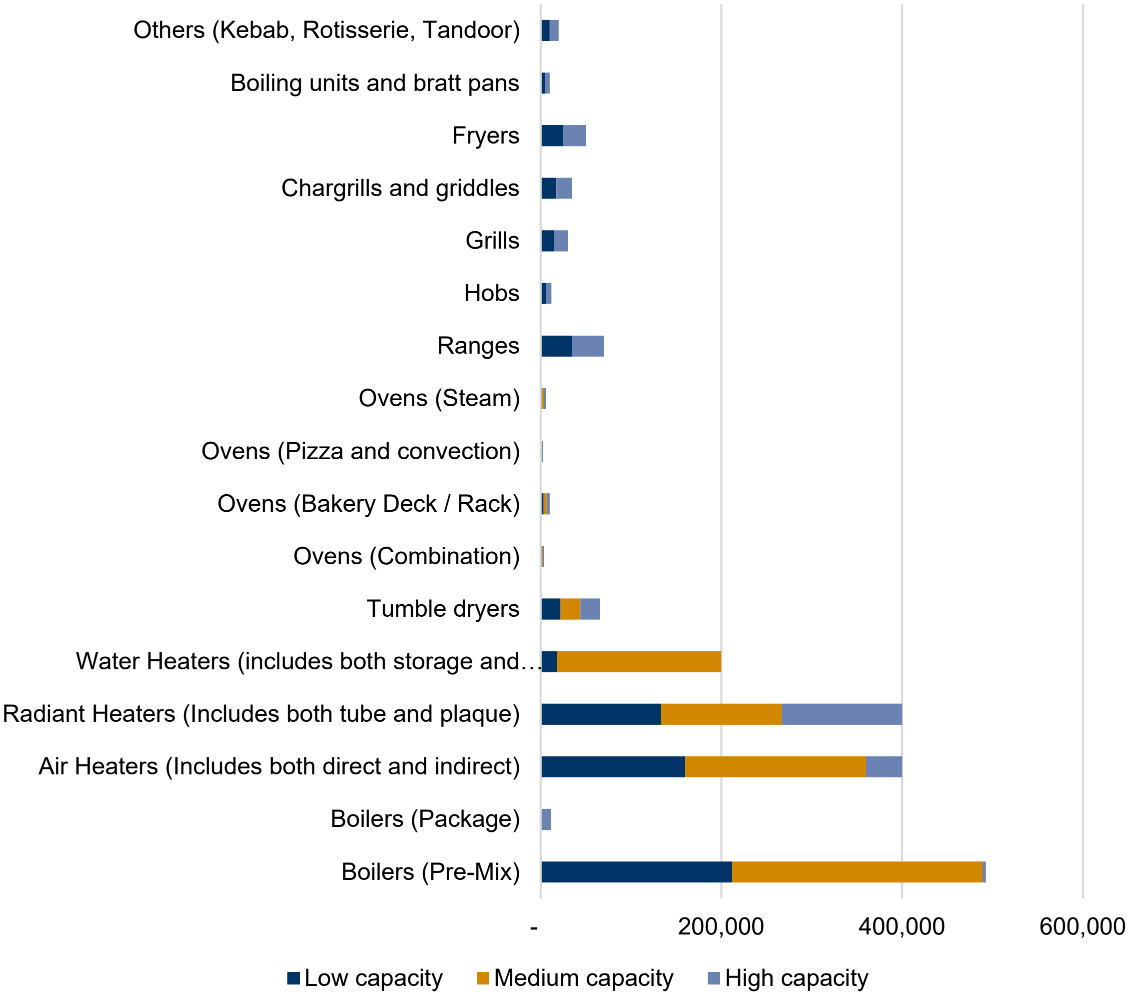
Table 7-1 – Appliance Definitions for Cost Model

Appliance #	Appliance type
Heating and Hot Water	
1	Boilers (Pre-mix)
2	Boilers (Package)
3	Air Heaters (Includes both direct and indirect)
4	Radiant Heaters (Includes both tube and plaque)
5	Water Heaters (Includes both direct storage and instantaneous)
6	Tumble dryers
Catering	
7	Ovens (Combination)
8	Ovens (Bakery Deck / Rack)
9	Ovens (Convection/Pizza)
10	Ovens (Steam)

Appliance #	Appliance type
11	Ranges
12	Hobs
13	Grills
14	Chargrills and griddles
15	Fryers
16	Boiling units and Bratt pans
17	Others (Kebab, Rotisserie, Tandoor)

The number of each type of unit which was assumed to be installed in the UK is summarised in Figure 7-2 below (the data table of values is provided in Appendix F). As costs would be expected to vary depending on the scale of the unit, the number of units was broken down into high, medium and low capacity ranges, with the relevant capacity of each range defined according to norms for that particular appliance type.

Figure 7-2 - Number of Each Type of Appliance in the UK



7.1.2 Research, Design and Testing Costs

7.1.2.1 Methodology

A summary of the methodology followed in order to analyse the costs associated with research, development and testing of the selected commercial appliance types is outlined below:

1. A top down approach was followed, with the R&D and testing costs at each stage derived from an overall cost to bring a new product to market.
2. Initial data points for the overall cost to bring a new product to market were taken from market research, which was then supplemented by data points provided by manufacturers, for example in the WP5 engagement event on 21 May 2019 ERM was verbally advised by Bosch that it takes £1.5-2m to bring a new appliance to market (i.e. TRL 1 to 9), however other manufacturers suggested much lower costs, for example £250,000-£350,000 for radiant heaters and £350,000-£500,000 for warm air heaters. As explained in Section 7.1.2.2, manufacturer feedback was gathered through several means, including a questionnaire, follow up calls and emails to clarify responses, and meetings such as the WP5 engagement event on 21 May 2019. Given the range of values provided by manufacturers, ERM applied its own sense check and research based analysis to manufacturer feedback.
3. The data points for overall development were divided over each TRL development stage, based on industry benchmarks for typical percentage cost incurred at each stage (see Table 7-2 below).
4. An additional factor was applied to cost to cover R&D and testing of conversion as well as replacement of the appliance. As there was no specific evidence for the magnitude of this factor it was refined later based on manufacturer feedback on whether the results of the analysis were considered too high/low (see section 7.1.2.2 for the explanation of forms of manufacturer feedback).
5. Factors were applied depending on the size and complexity of the appliance, reflecting the fact that larger appliances may require larger components, and more complex appliances will require more time and cost to develop. As there was no specific evidence for the magnitude of these factors they were refined later based on manufacturer feedback on whether the results of the analysis were considered too high/low.
6. The TRL was defined for each commercial appliance based on ERM's research and information received from manufacturers, and from this the % of R&D and testing cost remaining to take the appliance to TRL 9 was determined.
7. The results were sense checked against benchmark values from ERM's research and publicly available information. The values calculated by the model methodology for particular appliances were sense checked with manufacturers, and refined as information and feedback on the draft values was received from manufacturers. This then enabled refinement of the inputs and methodology to improve confidence in the analysis, for example when calculating the cost for appliances where there were gaps in information received from manufacturers.

7.1.2.2 Key Sources and Assumptions

TRL Definitions and Assumptions

The Technology Readiness Level (TRL) definitions and cost assumptions are summarised in Table 7-2 below. These assumptions were based on publicly available research[7], and the results of the analysis using these inputs was then sense checked with manufacturers.

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[7] For example: International Cost Estimating and Analysis Association (2017)

Table 7-2 – TRL Stages and Relative Development Expenditure

TRL	Definition	Development expenditure required	Level of development expenditure remaining
1	Basic principles observed and reported	0.9%	100%
2	Technology concept and/or application formulated	0.8%	99%
3	Experimental proof of concept	4.2%	98%
4	Technology validated in lab	7.7%	94%
5	Technology validated in relevant environment	11.0%	86%
6	Prototype demonstrated in relevant environment	14.5%	75%
7	Systems prototype demonstration in operational environment	17.9%	61%
8	System complete and qualified through test and demonstration	21.3%	43%
9	Actual system proven in operational environment	21.7%	22%

Review of Publicly Available Data

A review of publicly available data was undertaken in order to inform the analysis, and a selection of key sources used is provided below in Table 7-3. Note that the full list of references is provided in Section 9 “References” however this list provides a selection of the resources consulted in order to sense check the manufacturer responses and fill gaps.

Table 7-3 – Key Sources for Cost Model

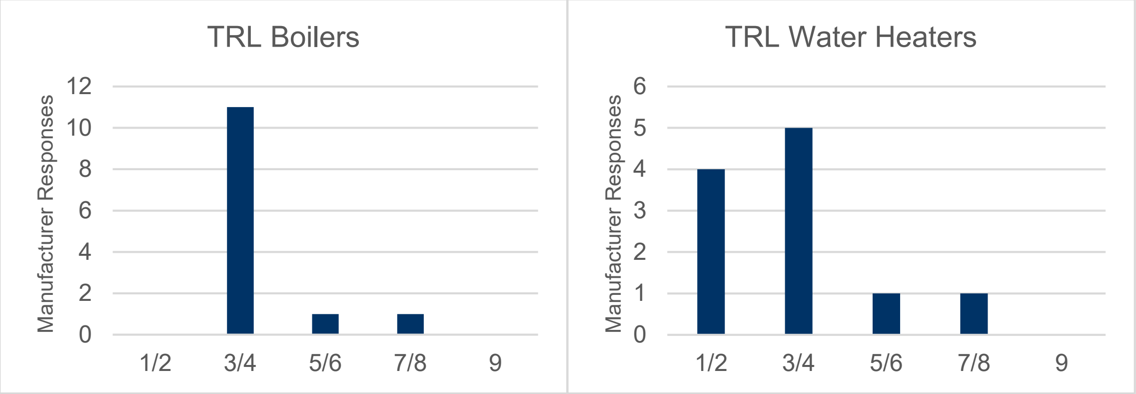
Appliance type	Reference	Web link	Data used from source
Boilers and catering appliances	Kiwa (2016) DECC Desk study on the development of a hydrogen-fired appliance supply chain	https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/537594/30686_Final_Report_DECC_Hydrogen_appliances_08.07.16.pdf	Estimated cost and timeline to develop 1st generation commercial boilers and catering equipment.
All	Element Energy presentation for BEIS (2018) Hydrogen Supply Chain Evidence Base	https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/760479/H2_supply_chain_evidence_-_publication_version.pdf	Supply chain readiness

Appliance type	Reference	Web link	Data used from source
All	H21 Leeds City Gate Team (2016) Report	https://www.northerngasnetworks.co.uk/wp-content/uploads/2017/04/H21-Report-Interactive-PDF-July-2016.compressed.pdf	Sense check of manufacturer inputs
All	International Cost Estimating and Analysis Association, presentation from 2017 ICEAA Professional Development and Training Workshop	http://www.iceaaonline.com/ready/wp-content/uploads/2017/07/DA05-PPT-Linick-Technology-Readiness-Level.pdf	Benchmark % investment required for each TRL

Data from Manufacturers

Information was sought from manufacturers in order to build the cost and timeline model, in several ways:

- Manufacturers provided responses to the questionnaire issued by ERM, and follow up questions posed by email and call.
- During the Hy4Heat WP5 engagement event on 21 May 2019 some high level views were provided verbally by manufacturers on research and development timelines and costing.
- Following the draft modelling, the initial inputs and results were presented to boiler and water heater manufacturers at an ICOM meeting on 07 August 2019 in order to validate and refine the analysis. For example, the assumed TRL of boilers and water heaters was posed to the attendees, with the results shown in the figures below.



7.1.2.3 Key Gaps in Information Made Available

Key gaps in the information made available are presented below in Table 7-4. In the table the following red/amber/green (RAG) categorisation has been used:

- Red: Very limited data points available, so ERM estimate used.
- Amber: Limited data points received, leading to gaps and limited confidence in the assumptions.
- Green: Sufficient information received to give acceptable confidence in assumptions.

Table 7-4 – Key Gaps in R&D and Testing Cost Model Inputs

Input	RAG Category	Comment	Modelling Approach
TRL of each appliance type	Green: Sufficient information received to give good confidence in assumptions.	Information only received from manufacturers on boilers and water heater TRL assumptions.	Similar TRL applied to other appliances, based on ERM analysis. Resulting costs sense checked against publicly available research.
Cost remaining to reach TRL 9	Amber: Limited data points received, leading to gaps and limited confidence in the assumptions.	Significant variation in manufacturer responses. Information received from manufacturers on radiant heaters and warm air heaters suggests £250-500k, while a catering appliance manufacturer suggested £100k (non-appliance specific) and another appliance manufacturer suggested £1.5-2m. Publicly available research suggests £2.5-3m[8].	Methodology developed based on ERM's research which was then sense-checked against manufacturer information. Priority was given to good quality manufacturer responses over publicly available research and verbal responses.

7.1.2.4 Results

The key results of the base case cost analysis are presented in Figure 7-3 below, with a table of the results provided in Appendix A. Note that for the purposes of this analysis the terminology "R&D" refers to TRL 1-5 (in other words from the basic principles being observed and reported to the technology being validated in relevant environment), while "Testing" refers to TRL 6-9 (in other words from the prototype being demonstrated in a relevant environment to the actual system proven in an operational environment).

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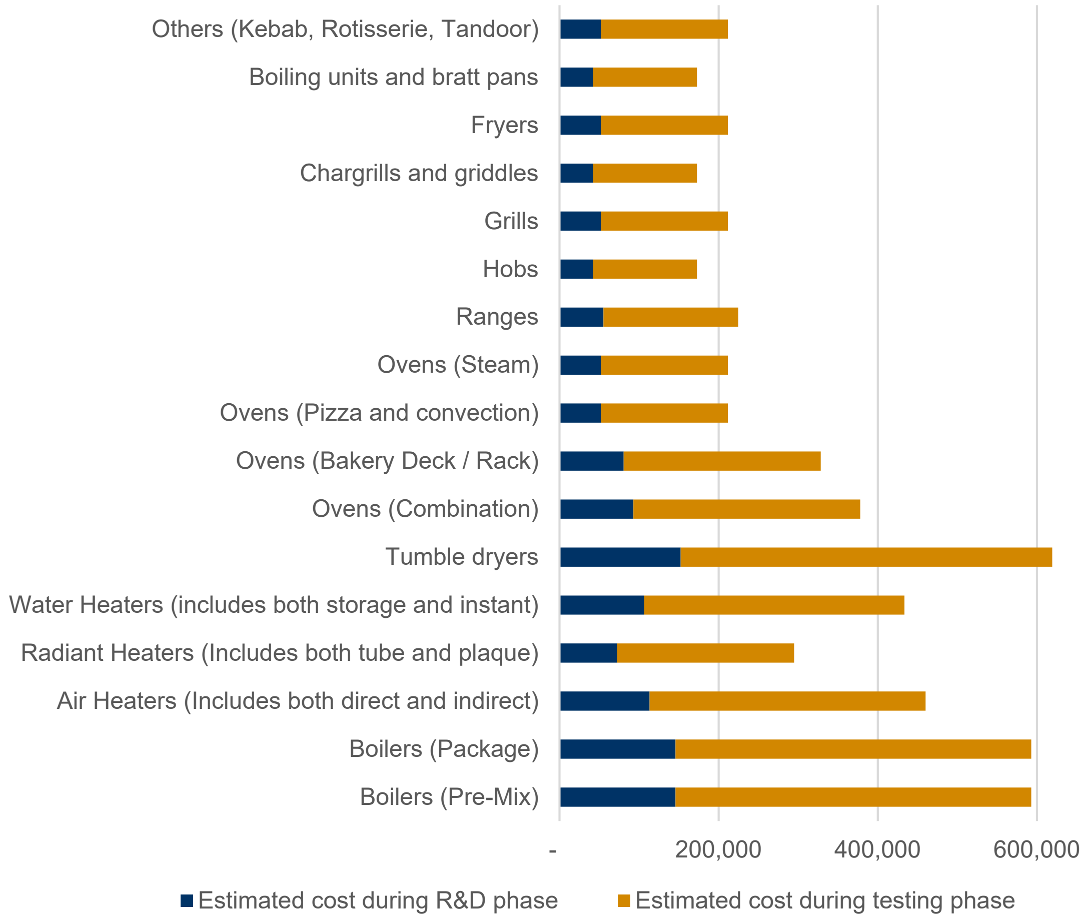
[8] For example Kiwa (2016)

Figure 7-3 - Estimated Cost for R&D and Testing



The total cost for research, development and testing of all 17 selected types of commercial appliance, from their current TRL to commercial readiness is estimated to be **£5.5m**.

As can be seen from Figure 7-3:

- R&D costs are estimated to be far lower than testing costs, reflecting the TRL of the appliances analysed and industry benchmarks indicating that the majority of costs are incurred during testing rather than R&D.
- The R&D cost varies very little between some of the appliances, reflecting the low level of data received to enable differentiation.

While there was relatively good quality information available for some appliances such as boilers, there were gaps in information provided by manufacturers which meant that the costs and timeline for some of the appliances was estimated based on publicly available information and the application of the methodology developed and sense checked for the other appliances. If further information is obtained from manufacturers then the analysis could be refined.

It should also be noted that as no one manufacturer produces all appliances, the cost estimates have been gathered from a range of manufacturers which may have different levels of information, risk averseness, perspectives on the likelihood of development of hydrogen gas grid and other subjective factors which could influence the cost estimate provided. Similarly, the willingness to invest in R&D by the manufacturer may be linked to the company size, financial performance and ownership structure. There may also be additional sunk costs such as upgrading existing test facilities to work with hydrogen which may or may not be reflected in particular manufacturer responses. As a result, care should be taken when using this analysis.

7.1.2.5 Conclusions and Recommendations – R&D and Testing

- The total cost for research, development and testing of the 17 selected appliances is estimated to be **£5.5m**. However as noted above this value should be considered with care is it does not take account of factors such as subjective impacts on cost estimates, corporate factors influencing R&D spend and differing sunk costs to upgrade testing facilities that may differ between manufacturers.
- BEIS may wish to undertake cost-benefit analysis in order to understand the most cost effective means of government support for these early stage costs. The potential economic advantages (for example GVA and job creation) of R&D support for manufacturers could be compared under a range of options, from limited support of a small fraction of the investment requirements to more significant government support of a higher percentage.
- The appliances with the most information available from manufacturers and publicly available research were boilers, air heaters and radiant heaters, while the appliances with the least information available were rotisseries and tumble dryers. It is recommended that manufacturers provide further information in order to refine the analysis.

7.1.3 Procurement and Installation Costs

The analysis of the cost associated with conversion or replacement of all installed commercial appliances in the 17 categories analysed is outlined below. As discussed in the Introduction to this section, the following terminology has been used to divide appliances into three categories:

- Appliances which need to be “replaced” because it is technically/economically unfeasible to convert to run on hydrogen.
- “Hydrogen ready” appliances which require only “Light” conversion costs in order to be able to run on hydrogen.
- Non-hydrogen ready appliances, which require “Heavy” conversion costs in order to be able to run on hydrogen.

7.1.3.1 Methodology – Conversion Cost

A summary of the methodology followed in order to analyse the cost associated with conversion of the selected appliance types is outlined below:

1. The cost of conversion was assumed to include several elements:
    a. Initial survey (flat cost for each unit)
    b. Labour for equipment conversion (calculated by time x rate, derived from complexity of conversion)
    c. Cost of components/equipment required for conversion (derived from complexity of conversion and appliance price)
    d. Ancillary works (for example conversion of pipework. Flat cost for each unit)
2. The cost of the initial survey (a.) was based on estimated time from publicly available research[9] and ERM's estimated labour rates based on publicly available information[10].
3. The cost of the ancillary works (d.) was based on publicly available research[11].
4. For each appliance type, a factor representing the complexity to convert between 1 and 10 was determined based on ERM research and manufacturer surveys. As there was no specific

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[9] For example Frazer Nash (2018) and H21 (2016)

[10] For example http://www.multi-trade.co.uk

[11] For example Element Energy (2018)

feedback on this factor from manufacturers, ERM created an initial approach based on publicly available research on the complexity of the appliances while was then refined based manufacturer feedback of the conversion costs produced by the methodology.

5. The labour to convert the appliance was based on the complexity and labour rate. This was then benchmarked against manufacturer responses and publicly available research.
6. The equipment cost to convert the appliance was based on the cost of a conventional (natural gas) appliance multiplied by a factor representing the complexity. This was then benchmarked against manufacturer responses and publicly available research.
7. The draft results were sense checked with manufacturers and publicly available research[12] such as H21 in order to refine the methodology and inputs, particularly for appliances and assumptions where only limited data was available.

A distinction was made between “Light” conversion of hydrogen ready appliances, and “Heavy” conversion of non-hydrogen ready appliances as summarised in Table 7-5 below.

Table 7-5 - "Light" Conversion Cost Comparison with "Heavy" Conversion

Cost Element	"Light" Conversion Cost as % of “Heavy”	Notes
Survey	50%	Assumes that 50% of survey activities are undertaken before the hydrogen ready appliance is installed (before the scope of this study)
Ancillary works	100%	Will be the same regardless of whether the appliance is hydrogen ready or not.
Equipment	50%	Conservative indicative assumption.
Labour	50%	Elements such as travel will be the same, but time to change out components will be reduced.

7.1.3.2 Methodology – Replacement Cost

Where it is technically or economically unfeasible to convert the appliance, the full replacement of the appliance would be required. The cost for replacement was calculated following a similar methodology to the cost for conversion, as outlined below:

1. The cost of replacement was assumed to include several elements:
   a. Initial survey (flat cost for each unit)
   b. Labour for appliance removal and new appliance installation (calculated by time x rate)
   c. Cost of replacement appliance
   d. Ancillary works (flat cost for each unit)
8. The cost of the initial survey (a.) was estimated in the same way as for the Conversion costs (explained above).
9. The cost of the ancillary works (d.) was estimated in the same way as for the Conversion costs (explained above).

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[12] For example H21 (2016)

10. For each appliance type, the cost of a conventional natural gas appliance was estimated from a range of sources such as online market places[13], research[14] and manufacturers. A factor was then applied to obtain the hydrogen appliance cost, based on publicly available research[15] and manufacturer surveys.
11. The labour to replace the appliance was based on publicly available research[16] and manufacturer responses.
12. The inputs and results were sense checked against publicly available research[17] and with manufacturers in order to refine the analysis.

7.1.3.3 Key Sources and Assumptions

Review of Publicly Available Data

A review of publicly available data was undertaken in order to inform the analysis, and a selection of key sources used is provided below in Table 7-6 (the full list is provided in Section 9 "References").

Table 7-6 – Key Sources for Procurement and Installation Cost Model

Appliance type	Reference	Web link	Data used from source
All	Element Energy presentation for BEIS (2018) Hydrogen Supply Chain Evidence Base	https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/760479/H2_supply_chain_evidence_-_publication_version.pdf	Ancillary works (pipework costs), materials and labour
All	H21 Leeds City Gate Team (2016) Report	https://www.northerngasnetworks.co.uk/wp-content/uploads/2017/04/H21-Report-Interactive-PDF-July-2016.compressed.pdf	Survey costs, parts costs, replacement costs for space heating
All	Frazer Nash (2018) Logistics of domestic hydrogen conversion	https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/760508/hydrogen-logistics.pdf	Survey costs, ancillary works costs
Air heaters	Preparatory Studies for Ecodesign Requirements of EuPs (III); ENER Lot 21 – Central heating products that use hot air to distribute heat; Task 2: Economic and Market Analysis; European Commission, DG ENER, July 2012	https://www.eceee.org/ecodesign/products/lot21-central-heating-products/	Device costs

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[13] For example: https://www.nisbets.co.uk/catering-appliances

[14] For example: https://www.eceee.org/ecodesign/products/lot22-23-kitchen/

[15] For example: KIWA (2016) and Element Energy (2018)

[16] For example: Element Energy (2018)

[17] For example: Element Energy (2018)

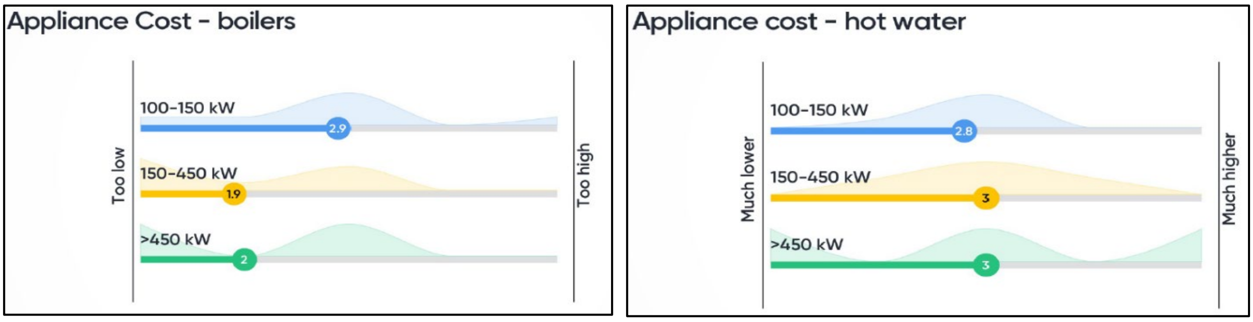
Appliance type	Reference	Web link	Data used from source
Radiant heaters	Preparatory Studies for Ecodesign Requirements of EuPs (III); ENER Lot 20 – Local Room Heating Products; Task 2: Economic and Market Analysis; European Commission, DG ENER, 25 June 2012	https://www.eceee.org/ecodesign/products/lot-20-local-room-heating-products/	Installation costs
Water heaters	EIA (2018) Updated Buildings Sector Appliance and Equipment Costs and Efficiencies	https://www.eia.gov/analysis/studies/buildings/equipcosts/pdf/full.pdf	Device costs
Tumble dryers	Preparatory Studies for Ecodesign Requirements of EuPs (III); ENER Lot 24 – Professional washers, dryers, dishwashers; Task 2: Economic and Market Analysis; European Commission, DG ENER, 25 June 2012	https://www.eceee.org/ecodesign/products/lot24-professional-wet-appliances/	Device costs
Ovens, ranges, hobs, grills, chargrills	Preparatory Studies for Ecodesign Requirements of EuPs (III); ENER Lot 22 – Domestic and commercial ovens (electric, gas, microwave), including when incorporated in cookers; Task 2: Economic and Market Analysis; European Commission, DG ENER, August 2011	https://www.eceee.org/ecodesign/products/lot22-23-kitchen/	Device costs
Catering appliances	Online marketplace	www.catering-appliance.com/shop	Device costs
Water boilers	Online marketplace	www.waterboilersdirect.com	Device costs

Data from Manufacturers

Information received from manufacturers was used to build and refine the conversion/replacement cost model at several stages of the modelling process:

- Manufacturers provided responses to the questionnaire issued by ERM, and follow up questions posed by email and call.
- Following the draft modelling, the initial inputs and results were presented to manufacturers at a WP5 roundtable on 07 August 2019 in order to validate and refine the analysis. For example, the assumed appliance cost of boilers and water heaters was posed to the attendees, with the results shown in the figures below (extracted from Mentimeter presentation software).

Figure 7-4 - Estimated Appliance Costs, Manufacture Feedback



7.1.3.4 Key Gaps in Information Made Available

Key gaps in the information made available are presented below in Table 7-7. In the table the following red/amber/green categorisation has been used:

- Red: Very limited data points available, so ERM estimate used.
- Amber: Limited data points received, leading to gaps and limited confidence in the assumptions.
- Green: Sufficient information received to give acceptable confidence in assumptions.

Table 7-7 – Key Gaps in Procurement and Installation Cost Model

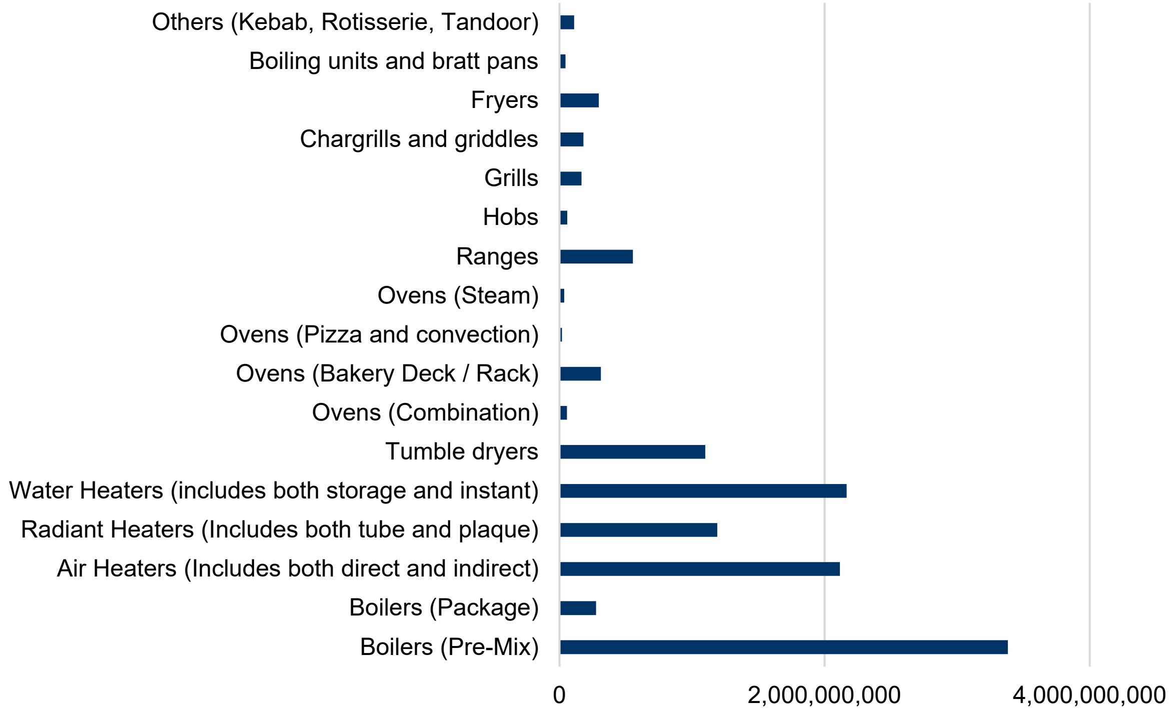
Input	RAG Category	Comment	Modelling Approach
Number of Appliances			
% of appliances which would be replaced, have “Light” conversion or “Heavy” conversion	🟥	The only direct feedback related to boilers (where conversion was not considered feasible). Verbal feedback (rather than documented) suggests for both heating and catering, opinion for transition is overwhelmingly “hydrogen ready” appliances or replacement with new H_2-only appliances. Retrofit ranked third. Lifetime of catering appliances is much shorter than heating so retrofit conversion not as critical.	Considered as a sensitivity for Monte Carlo analysis. Base case assumption is 50% replacement of boilers and 50% light conversion, while the other appliances have placeholder assumptions of 50% replacement and 25% each of light and heavy conversion.
Number of appliances of each type in the UK	🟨	The number of the following appliances are currently unknown: Rotisseries; Boiling units/bratt pans; Ovens (deck)	No data; set at zero.
Breakdown of number of appliances in the UK by size	🟩	The breakdown of number of appliances in the UK by size is unknown for all appliances except Boilers and Water Heaters.	Have made indicative assumptions.

Input	RAG Category	Comment	Modelling Approach
Number of Appliances			
Conversion			
Conversion: Labour time to convert appliances	🟥	Only one manufacturer data point of around 3 hours.	Considered as a sensitivity for Monte Carlo analysis. In base case have set all appliances close to manufacturer data point, with variation for complexity of appliance.
Conversion: equipment costs to convert appliances	🟥	Informal feedback is that manufacturers simply do not know how much needs to change, let alone where they would source the components and how much they would cost.	Considered as a sensitivity for Monte Carlo analysis. Base case input is based on value of appliance and complexity of appliance, sense checked with publicly available research.
Ancillary and survey fixed costs	🟩	Based on publiclypublicly available research to produce a 'per unit' cost.	It is recommended that further research is undertaken to understand potential savings from economies of scale
Replacement			
Replacement: Labour time to replace appliances	🟨	High-level information provided by manufacturers e.g. "Installations of a single item can take a number of men several hours" however no appliance specific info available so publicly available research has been used.	Considered as a sensitivity for Monte Carlo analysis. Base case has been set based on publicly available research on labour required and the complexity of the appliance.
Replacement: Cost for replacement appliance	🟨	Only three data points received for this, none of which are appliance specific. They are also very different, from 1.5x a natural gas appliance to "does not expect a huge difference."	Considered as a sensitivity for Monte Carlo analysis. Base case has been set based on publicly available research on the multiplier between a hydrogen appliance and natural gas appliance, and the current cost of a natural gas appliance.
Ancillary and survey fixed costs	🟩	As per Conversion assumptions	As per Conversion assumptions

7.1.3.5 Results

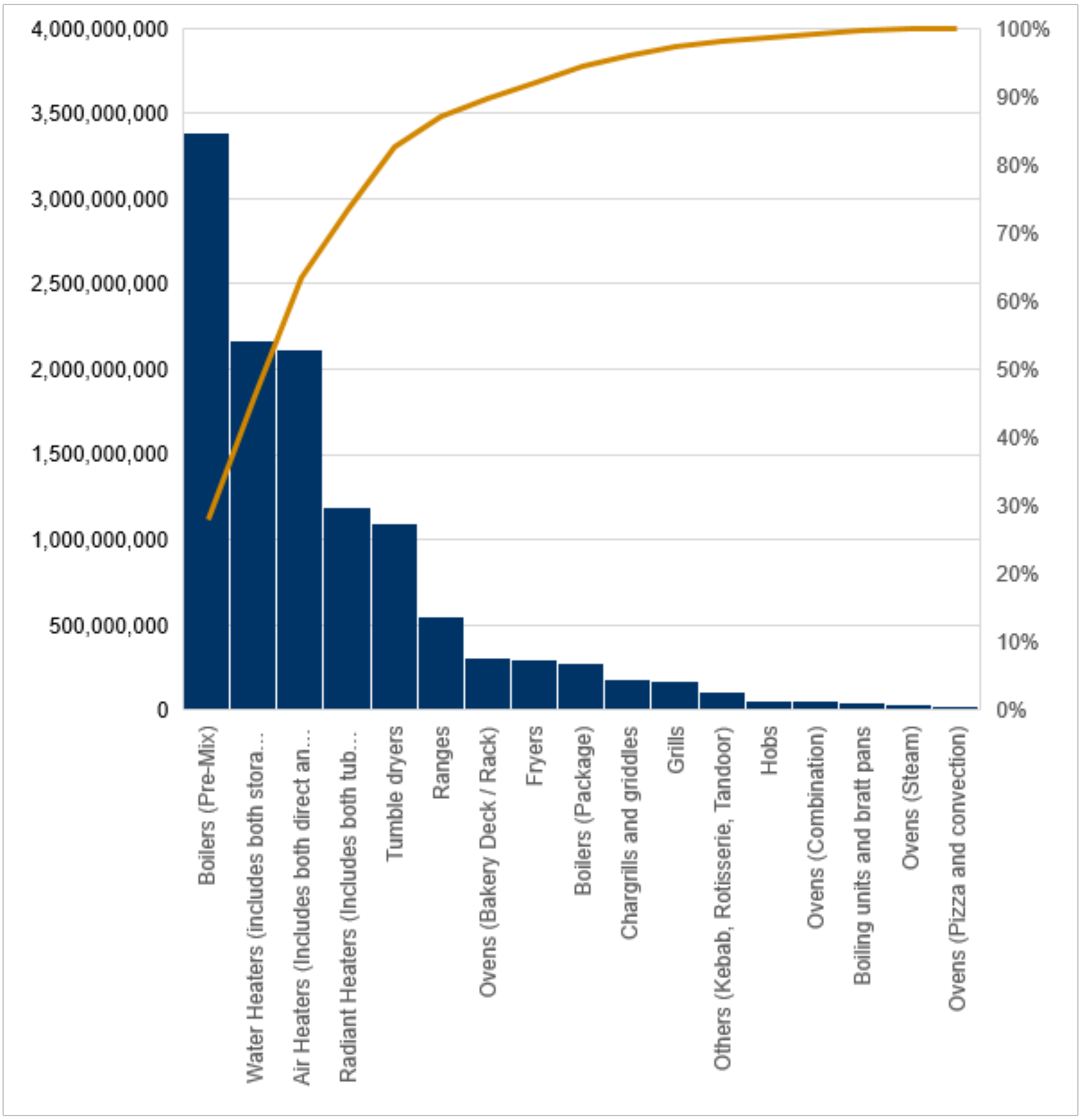
The key results of the analysis are presented in Figure 7-5 below, with a full breakdown of the cost per appliance in Appendix F.

Figure 7-5 - UK Capex to Convert or Replace Appliances (£)



A Pareto chart of the analysis is presented in Figure 7-6 below, which shows the appliances having the most effect on the overall cost.

Figure 7-6 – Pareto Chart of Appliance Replacement/Conversion Costs (£)



Total cost for replacement/conversion of all 17 selected types of appliance, from their current TRL to commercial readiness is estimated to be **£12bn**. Note that this value does not include the R&D and testing costs discussed earlier, it covers the conversion or replacement of installed appliances in the UK.

As can be seen from Figure 7-5 and Figure 7-6:

- The highest cost appliance to convert/replace has been estimated to be boilers (pre-mix), reflecting the relatively high number of units installed in the UK and the relatively high cost of replacement per unit.
- In contrast, hobs, steam ovens and pizza/convection ovens have relatively low costs, reflecting the relatively low number of installed appliances and relatively low cost of conversion or replacement per unit.

- The feasibility of converting non-hydrogen ready appliances rather than replacing them varies, with boilers considered to be technically and economically unfeasible to convert non-hydrogen ready appliances (so 50% replacement and 50% light conversion assumed) while other appliances are considered feasible so 25% heavy conversion of non-hydrogen ready appliances assumed. This reflects the feedback from manufacturers and ERM's analysis of publicly available research and component information.

Uncertainty Analysis

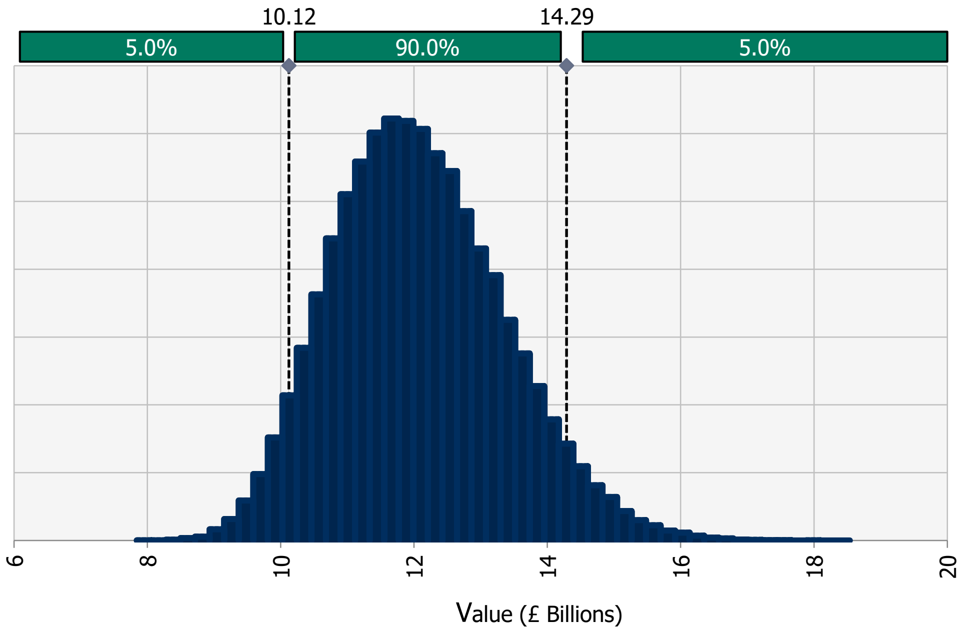
While there was relatively good quality information available for some appliances such as boilers, there were gaps in information provided by manufacturers of the less common appliances, which meant that the costs and timeline for some of the appliances were estimated based on publicly available research, ERM's analysis and the methodology and data points developed for the other appliances.

The uncertainty associated with the benchmark costs has been investigated using Monte Carlo analysis around the key inputs impacting the results, for which there was most limited data available:

- The impact of complexity of conversion on labour time
- The impact of complexity of conversion on equipment cost
- Survey cost for both conversion and replacement
- Ancillary works cost for both conversion and replacement
- The factor increase for a hydrogen appliance price compared to natural gas appliance
- Hours required for installation of replacement appliance
- The number of each type of appliance installed in the UK

The key assumptions used in the Monte Carlo analysis of these variables is summarised in Appendix A. The results of the Monte Carlo analysis are shown in Figure 7-7, Figure 7-8 and Figure 7-9 below.

Figure 7-7 – Estimated Cost Range to Convert or Replace All UK Appliances



As can be seen from Figure 7-7, the Monte Carlo analysis indicates a 90% chance of costs being between £10.12bn and £14.29bn. Figure 7-8 below is a tornado diagram showing the inputs ranked in order of their value impact on the mean total cost to convert or replace all UK appliances, while Figure 7-9 shows the percentage contribution of each input. As can be seen from the figures, the total cost to covert or replace all Commercial appliances in the UK is most sensitive to the hydrogen:natural gas appliance price multiplier, followed by the percentage of boilers (premix) which are replaced, , and ancillary costs.

Figure 7-8 – Tornado Diagram of Contributors to Total Cost Mean

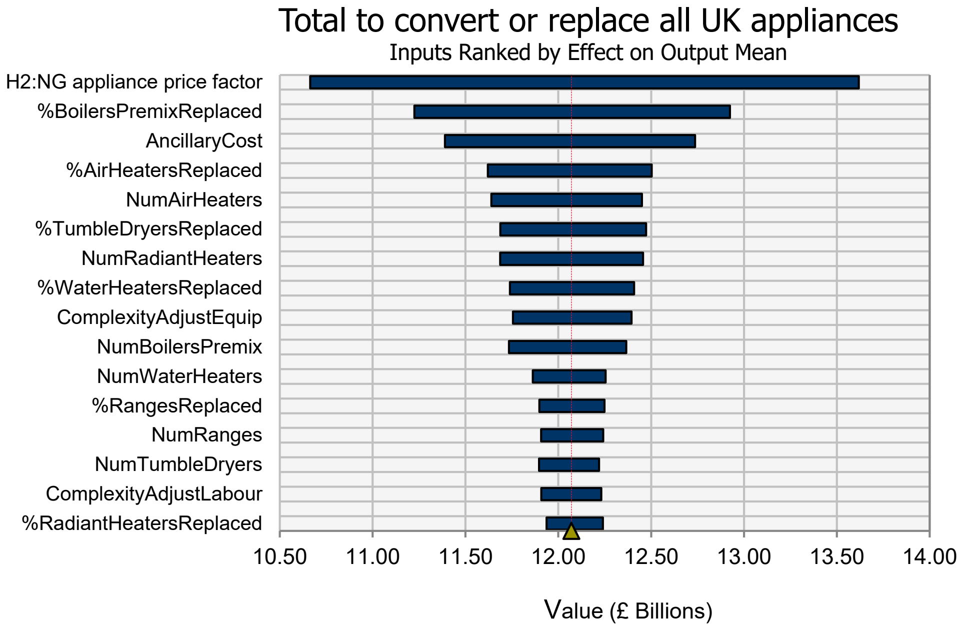
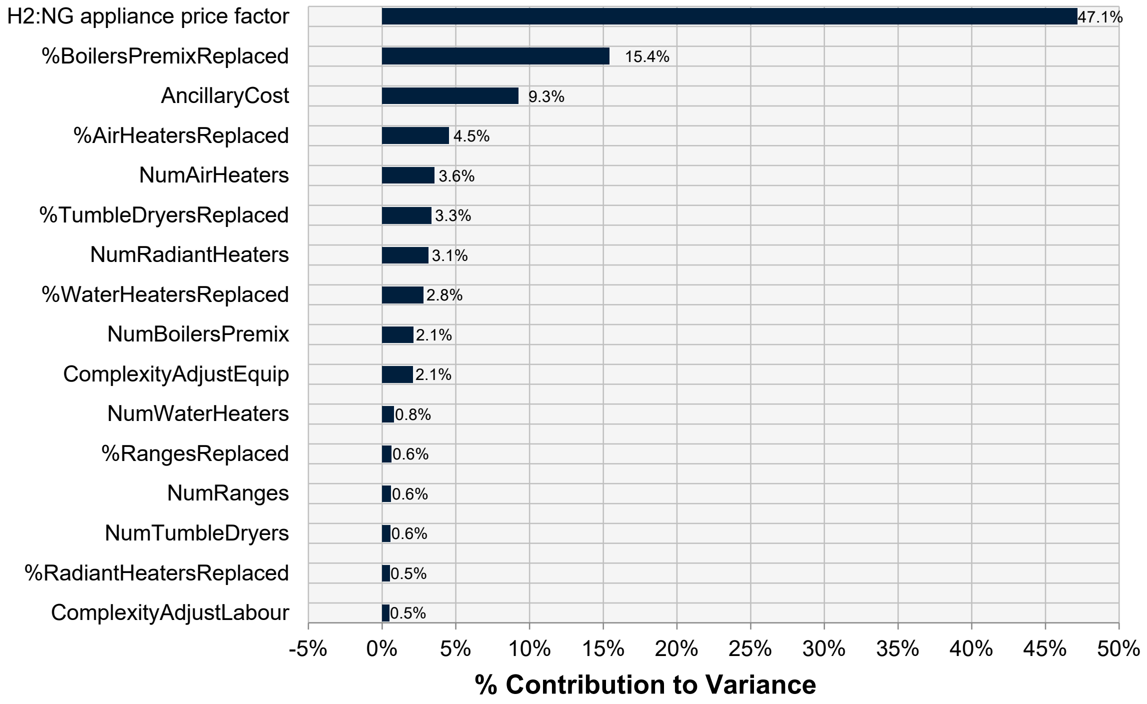


Figure 7-9 – Contributors to Total Cost Variance



7.1.3.6 Sensitivity Analysis on Cost of Hydrogen Appliances Compared to Natural Gas Appliances

The methodology used to calculate conversion and replacement costs is aligned with the publically available research and feedback from manufacturers that was available when the study was conducted. Subsequently, the messaging from early mover manufacturers on domestic hydrogen fuelled boilers has become more positive, and so a sensitivity was run to reflect the possibility that the cost of commercial hydrogen heating appliances could be lower than the assumptions made in the base case.

Originally a factor of 1.5 was applied to the natural gas appliance cost in order to estimate hydrogen appliance cost, based on publically available research18. However, the feedback received from manufacturers[19] indicated that the estimated costs resulting from this were too low, and so the factor was increased and refined for each appliance sizing bin.

Since the base case analysis was undertaken, two manufacturers have messaged publically20 that domestic hydrogen boilers may not have costs which are significantly different from natural

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[18] For example Kiwa, 2016, which states "Third generation commercial appliances may cost 1.5 times natural gas". Available at: https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/537594/30686_Final_Report_DECC_Hydrogen_appliances_08.07.16.pdf

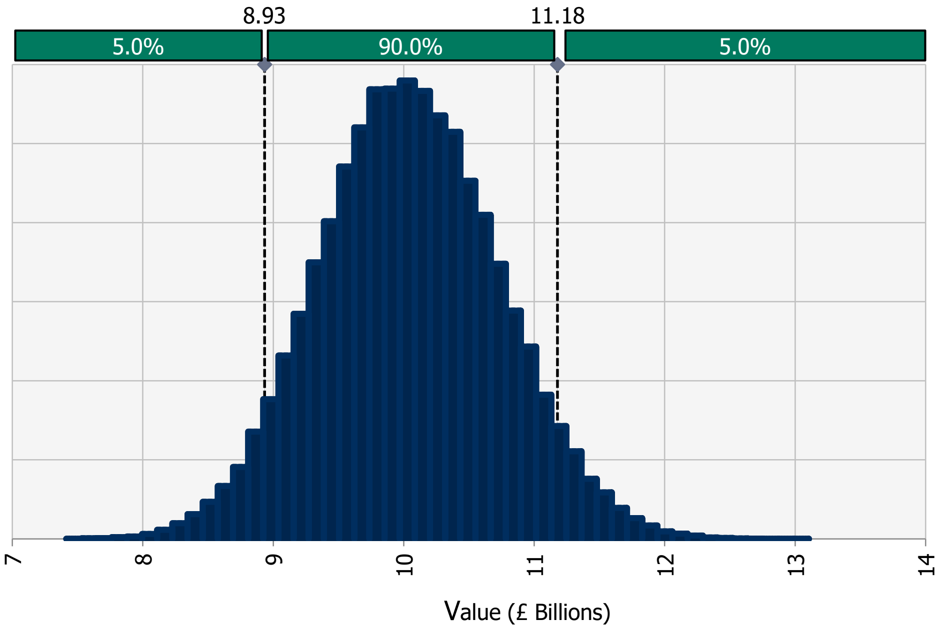
[19] For example in the WP5 Roundtable

[20] For example: *"Initially, hydrogen-ready boilers may cost £50-£100 more than conventional natural gas boilers" (*At https://www.cibsejournal.com/technical/fuel-for-thought-hydrogen-gas-boilers/, accessed 14 August), and https://www.worcester-bosch.co.uk/hydrogen accessed 14 August 2020 states: *"There is no reason why, at similar scale,*

gas boilers. Although this view has not been provided formally to the study, it indicates that it would be appropriate to run a sensitivity with a lower cost assumption than the base case. As a result, a sensitivity case has been run assuming a factor of 1.5 uplift from natural gas appliance costs as an estimate for hydrogen appliance costs.

The results are summarised in Figure 7-10 below, and as can be seen the resulting costs of between £8.93 and £11.18bn are significantly lower than the base case. This sensitivity case highlights the fast-moving nature of development in this field and the potential for costs to significantly reduce over time.

Figure 7-10 – Total to Convert or Replace All UK Appliances (Sensitivity)



7.1.3.7 Conclusions and Recommendations – Conversion/Replacement

- The total cost for replacement or conversion of all units of the 17 selected appliances installed in the UK is estimated to be **£12bn**, based on engagement up to August 2019 with water heating appliance manufacturers. This analysis was based on a 'per unit' cost multiplied by number of units, and it is recommended that further analysis using scaled community trial conversion/replacement is undertaken in order to firm up the costs and establish potential cost saving measures such as those which could arise from economies of scale and conversion/replacement of multiple units in the same premises.
- When more recent water heating manufacturer messaging is factored into calculations, the total cost for replacement or conversion of all units could be potentially be as low as **£9bn.**
- The appliances with the most information made available by manufacturers were boilers, air heaters and radiant heaters, while the appliances with the least information available were rotisseries and tumble dryers. To some extent these gaps reflect the fact that manufacturers may simply not know the answers to the questions posed. Further analysis of the appliances

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hydrogen-ready boilers should not reach a similar cost to natural gas boilers today. The ancillary components, accessories and controls will be identical to those for natural gas boilers."

associated with the most uncertainty is recommended in order to refine the assumptions used in the analysis.

- The cost of a new appliance which can run on 100% hydrogen when compared with an existing natural gas appliance was a key uncertainty associated with the analysis. A base case factor was applied based on feedback from manufacturers and publicly available research.[21] Monte Carlo analysis suggests this is a key influence on the cost estimates, therefore it is recommended that further research is undertaken in this area.
- The scale and timing of development of “hydrogen ready” appliances is a key unknown. If wide scale rollout of these appliances was achieved, for example in catering appliances which have a relatively low lifetime compared with boilers, then the conversion costs would be expected to be significantly lower than conversion of non-hydrogen ready appliances. Further research in this area is recommended, for example BEIS may wish to consider how the UK conversion costs may reduce under a range of scenarios in which differing levels of early stage support and policy signals are used to support the development of hydrogen ready appliances.
- The survey and ancillary works costs used in the modelling of conversion and replacement were based on publicly available research[22] in order to establish per unit values. It is recommended that further research is undertaken in order to refine these costs, for example through community demonstration trial in order to establish for example cost savings arising from economies of scale and conversion/replacement of multiple units in the same premises. Monte Carlo analysis suggests that ancillary works costs in particular are a key influence on the cost estimates, and it is notable that estimates for this cost varied significantly in publicly available research[23].
- The model methodology used to calculate equipment and labour costs for conversion is based on the complexity of the appliance and the appliance value. Similarly, the labour cost for replacement is based on publicly available research.[24] There were very limited data points to determine these values and so they follow a fairly linear relationship with the equipment value, it is recommended that manufacturers provide further information in order to refine these estimates further.

7.1.4 Timing

7.1.4.1 Methodology

A summary of the methodology followed in order to estimate the timing associated with R&D and testing, and conversion/replacement of all 17 types of appliance analysed is outlined below:

1. The % of expenditure required and overall timeframe to reach TRL 9 from TRL 1 for a new appliance was defined based on publicly available research and information from manufacturers.
2. The current TRL of each appliance was used to generate an estimate of the remaining time to reach TRL 9.
3. Earliest kick off of the Procurement, Installation and Commissioning was aligned with the phased rollout envisaged by H21, which suggests a start date in 2028 in Leeds. If policy decisions support a framework aligned with the approach envisaged in H21 then conversion of commercial appliances could begin in 2028, hence that was taken as the base case assumption.

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[21] For example Kiwa (2016) and Element Energy (2018)

[22] For example Frazer Nash (2018), H21 (2016) and Element Energy (2018)

[23] For example £1,000-£5,000 for internal pipework cost for commercial boiler estimated by Element Energy (2018) and £100 for pipework at a domestic property estimated by H21 (2016)

[24] For example Element Energy (2018) and H21 (2016)

4. The draft assumptions and results were sense checked and firmed up based on feedback from manufacturers.

7.1.4.2 Key sources and assumptions

Review of Publicly Available Data

A review of publicly available data was undertaken in order to inform the analysis, and a selection of key sources used is provided below in Table 7-8 (for the full list please see Section 9 "References").

Table 7-8 – Key Sources for Timing Estimate

Appliance type	Reference	Web link	Data used from source
Boilers and catering appliances	Kiwa (2016) DECC Desk study on the development of a hydrogen-fired appliance supply chain	https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/537594/30686_Final_Report_DECC_Hydrogen_appliances_08.07.16.pdf	Estimated timeline to develop 1st generation commercial boilers and catering equipment.
Domestic boilers	Element Energy presentation for BEIS (2018)	https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/760479/H2_supply_chain_evidence_-_publication_version.pdf	Timeline for domestic boilers
All	H21 Leeds City Gate Team (2016) Report	https://www.northerngasnetworks.co.uk/wp-content/uploads/2017/04/H21-Report-Interactive-PDF-July-2016.compressed.pdf	Rollout across UK from 2026 (Leeds) to 2045 (London)
All	H21 North of England (2018) Report	https://www.northerngasnetworks.co.uk/wp-content/uploads/2018/11/H21-Meeting-UK-Climate-Change-Obligations.pdf	Rollout across UK from 2028 with expansion across cities in N England over seven years. Further six phase rollout to convert rest of country by 2050.

When considering the optimum way to rollout the conversion of the gas network several factors will need to be considered. These include:

- Acceptable duration for customers to be without gas;
- The size of the conversion workforce;
- The ability and cost of maintaining temporary supplies through options such as liquid natural gas and potentially bottled gas for short periods; and
- The number of isolations required.

For the commercial sector, it should be noted that commercial premises are generally co-located with residential premises within the gas network. This co-location ties the conversion of commercial appliances to the same timeline as domestic appliances. It is further noted that there are many 'commercial zones' where the majority of premises are commercial. However, these zones will likely need to be converted in the same staged geographical manner and within a similar timeframe as the neighbouring grid sections to minimise the requirement for temporary supplies (if the commercial zone is isolated from the existing natural gas supply to allow for conversion of neighbouring zones).

Similarly, the individual commercial appliances types are found in a wide variety of commercial premises, for example, schools often have at least one commercial gas boiler, commercial water heater, dry heating unit and commercial catering appliances. Therefore it is not considered feasible to convert based on appliance type.

The ability to provide temporary supplies, and the associated cost involved, must be carefully considered for commercial premises. Many commercial premises are high intensity consumers, use gas for heating more hours per week, and have a higher criticality for security of supply (e.g. hospitals).

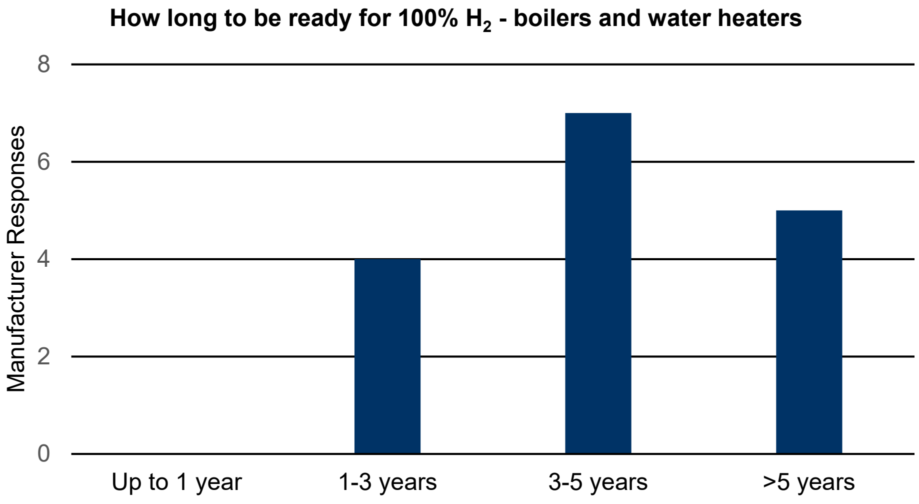
The staged network conversion based on geographical layout described in the H21 NoE and LCG reports is considered to be the most credible method for conversion of the commercial sector and has been used as the basis for the cost model in this study. In order to successfully convert the commercial sector, it is vital that the development timelines for commercial appliances are able to closely match those of domestic appliances so that the commercial sector is not left behind.

It should be noted that this model has made no attempt to quantify the costs involved with providing temporary supplies to commercial users during the staged conversion process.

Data from Manufacturers

Information was received from manufacturers and used to develop and validate the timeline model, including by means of the questionnaire and follow up data requests, and Hy4Heat stakeholder workshop and roundtables. For example, the assumed timeline for boilers and water heaters was posed to the attendees, with the results shown below in Figure 7-11.

Figure 7-11 – Timeline Estimates for 100% Hydrogen Boilers and Water Heaters



7.1.4.3 Results and Recommendations

An indicative timeline is presented in Figure 7-12 below.

Figure 7-12 – Overall Timeline for Conversion of the Commercial Sector

Phase	Length of Phase (Years)	Year 1	Year 2	Year 3	Year 4	Year 5	Year 6	Year 7	Year 8	Year 9	Year 10	Year 11	Year 12	Year 13	Year 14	…	Year 29
R&D & Testing	5	🟩	🟩	🟩	🟩	🟩											
Procurement	24						🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩
Installation	22								🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩
Commissioning	22								🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩

Key milestones in the timeline are as follows:

- Research, development and testing for all of the commercial appliances considered as part of this analysis could be completed within 5 years, assuming policy makers signal a firm plan for conversion or replacement of all gas appliances in the UK to 100% hydrogen. Much faster action is possible, with many manufacturers signalling 2 years for some appliances while the majority are in the 3-5 year bracket. Feedback from manufacturers suggests that heating appliances need two seasons for testing, while catering appliances can potentially reach market much faster. However the key enabler and driver of this activity would be policy signals related to the conversion of the UK hydrogen network and therefore creation of a market for 100% hydrogen appliances.
- Installation of the equipment, including conversion or replacement, could only occur once all appliance variants were commercially available and the necessary upstream infrastructure is commissioned. This could occur as early as 7 years, similar to that assumed in H21's North of England (NoE) report[25]. A phased geographic approach to rollout is assumed in line with the timeline envisaged by H21 NoE. As with the R&D and testing stage, faster rollout would be possible given strong government support. If the development of hydrogen ready appliances requiring only light conversion is facilitated, through clear policy signals and early stage R&D and testing funding support, then faster conversion with shorter phases would be facilitated.

Uncertainty Analysis

While there was relatively good quality information available for some appliances such as boilers, there were gaps in information provided by manufacturers of the less common appliances, which meant that the timeline for most of the appliances was estimated based on publicly available research and ERM's analysis.

As the timeline is primarily driven by regulatory signals to incentivise the development of the market, it was not considered meaningful to undertake Monte Carlo analysis for timing in the same way as the cost analysis. Instead policy makers may wish to consider a number of different options for supporting the development of the hydrogen market and conversion of the UK gas grid, and the policy enablers required in order to achieve particular target timelines.

7.1.4.4 Conclusions and Recommendations - Timing

- The timeline for research, development and testing of the selected 17 commercial appliances will be driven by the signalling of government support for the conversion of the gas grid and therefore the creation of a market for hydrogen appliances. Assuming these policy signals are put in place, research, development and testing could be completed within 5 years, with the potential to be sooner with the right policy signals.

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[25] H21 (2018) North of England, https://www.northerngasnetworks.co.uk/wp-content/uploads/2018/11/H21-Meeting-UK-Climate-Change-Obligations.pdf

- Replacement or conversion of all units of the 17 selected appliances installed in the UK is estimated to take place 7 years after the start of the R&D phase, and occur in a phased approach. Refer to Section 7.1.4.3 for further discussion of phased approach options. This analysis is based on high-level assumptions around government support and the creation of a hydrogen market. Policy makers may wish to consider a number of different options for supporting the development of the hydrogen market and conversion of the UK gas grid, and the policy signals required to achieve the target timelines.

7.2 Planning for a Small Community Trial

One of the principal objectives of the Hy4Heat project is planning for a potential small community trial using appliances developed to run on 100% hydrogen. The findings of this report can be used to inform the decisions about which appliances to develop and what the small community setting should include in order to gain the best indication of the feasibility of successfully converting the commercial sector to hydrogen.

7.2.1 Key Considerations

The key factors which should be considered when planning for a small community trial of hydrogen fired commercial scale appliances are discussed below.

Most common appliance types

Identifying the most commonly used appliances in the commercial sector is the first key consideration. The trial should ensure that these appliances are included, or at the very least, the key components and appliance functionality, are represented.

The data presented in Section 4.5.2 can be used to identify the most common appliances currently installed in the UK.

Unique appliances/components

In order to successfully convert the commercial sector, all users of mains natural gas must be able to switch the appliance to either hydrogen or another low carbon energy source. Appliances which are unique to the commercial sector and where no alternative appliance type is available should be considered for inclusion in the trial.

Largest consumers of natural gas

The largest consumers of natural gas in the commercial sector should be considered when selecting appliances and settings for the trial. Space heating has been identified as the largest use type, however the end use setting should also be considered. Energy consumption statistics from BEIS summarised in Section 4.2 and in more detail in Appendix B show the largest consumers of natural gas to be offices, hospitals and factories.

Most natural gas appliances installed in commercial premises

Another factor which should be considered is the number of sites in the UK where the commercial appliances are installed. By successfully demonstrating that the hydrogen appliance function safely and effectively in a setting which is known to have many natural gas appliances, the confidence level in the ability to successfully convert the commercial sector can be increased.

Data summarised in Section 4.5 and presented in more detail in Appendix B show that boilers are most likely to be found in small retail shops, private offices, schools and offices. Warm air and radiant heaters are most likely to be found in industrial settings such as factories and workshops.

Most critical in terms of use

The reliance on the appliances covered in this study to provide heat for comfort, hot water and food in commercial settings varies from low to critical. Many commercial users rely on heat for comfort, and the loss of heat would simply be an inconvenience to the business. However there are end users where heat is a critical service to the function of the business. Such users include hospitals where patient well-being, and sometimes survival, is dependent on space heating. Demonstrating that hydrogen appliances can safely and reliably deliver space heating continuously over a long period will help to prove the case that the commercial sector can be successfully converted.

Largest contributors to sector conversion cost

The cost of conversion analysis presented in this report should also be considered when planning for a community trial. By including those appliances whose development contributes the greatest to the cost of converting the commercial sector, both in terms of absolute cost and uncertainty, this gives industry the opportunity to commence research and development of these appliances and potentially develop solutions which are more effective and cheaper than currently predicted.

The analysis in Section 7.1 shows that the cost of converting commercial boilers is the single largest contributor to overall cost, and that the percentage of commercial boilers which must be replaced by a new hydrogen appliance rather than converted from a hydrogen-ready state is the largest contributor to uncertainty in the cost estimate. The development of hydrogen-ready appliances for use in the trial could lead to a much wider range of hydrogen-ready commercial appliances being available and installed by the time of conversion, with the expectation that this would decrease the overall cost of converting the commercial sector.

7.2.2 Suggested Development and Deployment Plan

Taking account of the considerations in previous section, a suggested development and deployment plan is provided below for the most likely commercial scale appliances to be found in a small community trial.

Appliance Selection

The commercial scale appliances which should be included in a small community trial, with justification, are:

- Light commercial boiler (<70 kW) installed in cascade arrangement of two or more units
    - Boilers are the single largest consumer of natural gas and the most common appliance installed in the commercial sector. Proving the successful function of cascaded units will provide the confidence that cascade arrangements can fulfil the space heating requirements of large commercial premises such as hospitals and prisons.
- Warm air heater
    - Warm air heaters have no domestic equivalent, and therefore no development already underway as part of other Hy4Heat work packages. They are one of the most commonly found appliances in the commercial and industrial sectors, contributing a large amount to current levels of natural gas consumption.
    - There are potential issues with meeting future eco-design regulation efficiency and emissions targets concurrently for current natural gas warm air heaters, so the early development of a hydrogen appliance which can meet the requirements of GAR and
- Radiant tube and/or radiant plaque heater
    - Radiant tube and radiant plaque heaters have no domestic equivalents, and therefore no development already underway as part of other Hy4Heat work packages. They

are two of the most commonly found appliances in the commercial and industrial sectors, contributing a large amount to current levels of natural gas consumption.

- Catering appliances:
    - Range
        - Ranges are the most commonly found commercial catering appliance in UK commercial kitchens. This is a function of their durability and versatility, being able to perform most of the methods of cookery required by chefs.
        - The basic technology for a range in terms of burner design and safety features appears common to the domestic hob and oven already under development as part of Hy4Heat Work Package 4. However, a commercial range is required to produce considerably more food over the course of a day, so the burners are generally more powerful and must be more robust. Therefore the durability and reliability of a hydrogen appliance should be displayed as well as the safety and functionality.
    - Fryer
        - Fryers are the second most common commercial catering appliance, found in a wide variety of commercial kitchens. Deep frying is a technique that is used in fast food restaurants through to fine dining establishments.
        - There is no equivalent domestic appliance, and therefore demonstration of a safe and functioning fryer is considered to be valuable. It is noted, though, that the basic components of a fryer are shared with other commercial catering appliances, including both atmospheric and forced draft burner types. Similarly, electric variants of the salamander grill are in use widely. Therefore the driver for including a fryer is more a function of the popularity of the appliance and its cooking method than development of the technology.
    - Grill
        - Salamander grills utilise a radiant plaque burner which make them unique to the commercial sector. While electric variants currently exist, development of a hydrogen grill is recommended to provide future choice for an appliance which uses considerable energy within commercial kitchens.
    - Chargrill
        - Chargrills as an appliance are unique to the commercial sector, however the basic componentry is not necessarily unique. While electric variants do exist, the vast majority of chargrills sold in the UK are gas. This is a results of the ability to ‘flame grill’ food to give it a desirable texture and flavour.
    - Combination oven
        - Combination ovens are not entirely unique to the commercial sector, with some domestic ovens now able to provide a steam function within the traditional convection oven. However, there is no known development of a domestic oven with steam function using hydrogen.
        - Commercial scale combination ovens are much larger and are equipped with much more advanced control than domestic steam ovens. These combination ovens are able to cook a wide variety of dishes at the same time, to a high level of quality, with a high capacity for meals served per day making them popular in high end restaurants and catering kitchens alike.

- Electric combination ovens are widely available, however the electricity requirement for these ovens is very large, and may be prohibitive in some premises.
- It is noted that development times for a hydrogen combination oven may be prohibitive given the advanced control requirements. A more basic steam oven, while not as popular in commercial kitchens, may be suitable alternative for proof of concept.

Site Selection

The choice of site for a small community trial should consider the variety of premises which are present in the UK commercial sector. The data presented in Appendix B includes the number of each type of commercial premise as reported in the BEES study [3]. This can be used to identify the most common types of commercial premises, and when combined with the estimated

Knowledge of the gas usage requirements within the non-domestic premises should be used to inform site selection. The key differentiator for domestic and commercial gas consumption is intensity and duration. Commercial premises are generally larger, requiring a significantly larger peak heating load. In addition, CIBSE guidance [12] shows that some commercial premises such as hospitals and hotels require up to 3,500 hours of equivalent full load space heating per year. The type of space heating required is also different within the commercial sector, with large buildings using warm air or radiant heating to provide heat where traditional wet central heating systems are not effective.

If a single site is to be selected, the site should have the following buildings to prove the key heating requirements of the commercial sector:

- Large indoor space where wet central heating is required (e.g. offices).
- Large indoor space where radiant heating is required (e.g. gymnasium)
- Large indoor space where warm air heating is required (e.g. workshop)
- On-site kitchen providing large number of meals per day

Using the above criteria, a single site which is likely to fulfil all of the requirements includes:

- School
- University
- Prison
- Hospital
- Fire station

Alternatively, a small village or commercial centre could be selected, thereby allowing for more end use settings to be included. A study should be commissioned, or nomination process commenced, to identify the most suitable location which covers the most representative spread of commercial premises.

8. CONCLUSIONS AND RECOMMENDATIONS

8.1 Main Findings

Market Characterisation

The market study conducted for WP5 was arguably the largest and most in depth consideration of natural gas appliances in the UK commercial sector to date. Engagement with key stakeholders revealed that sector level population data does not exist for most appliances, and that the commercial sector is heavily segmented, reflecting the diversity of the commercial appliance market.

The installed market for commercial natural gas fired heating appliances is estimated to be 1.5 million units (likely range 1.0 – 2.0 million units) within the 2.0 million non-domestic premises in the UK. The wide range of the estimate reflects the level of uncertainty in the input data used for this study, which was derived from a combination of sources.

Natural gas consumption for heating in the commercial and industrial sectors totalled 103.6 TWh in 2017, with the major uses being space heating (78%), hot water (9%) and catering (6%). In line with the consumption data, space heating appliances are the largest contributor to the overall installed base.

Boilers are the most populous appliance in the commercial sector, with an estimated installed base of approximately 500,000 commercial sized units (30 kW – 1 MW). Dry space heating appliances are the next most populous, with an estimated 300,000 warm air heaters and 300,000 radiant heaters currently installed.

It is estimated that there are 200,000 gas fired commercial water heaters in the UK providing sanitary hot water.

Confidence in the estimates for installed base of boilers and water heaters is high, as a result of the aggregated sales data maintained by the relevant trade body. Confidence in the estimates for warm air and radiant heaters is lower, since aggregated sales data is not kept for these appliance types.

There are an estimated 250,000 gas fired commercial catering appliances installed in commercial kitchens in the UK. Ranges are the most common, due largely to their versatility, followed by fryers and salamander grills. However, as there is no industry aggregated sales data for commercial catering appliances, confidence in the population estimate is low.

An estimated 66,000 gas fired tumble dryers are installed in numerous commercial settings, including universities, prisons, laundrettes and hospitals.

The relative distributions of gas fired commercial appliances within the commercial subsectors and end use settings is not well known. The exception to this is boilers in the public sector, due to the significant amount of data obtained from of a large Freedom of Information (FOI) campaign carried out as part of the market study.

It is estimated that up to 80% of all commercial boilers are less than 150 kW rated input. Up to this size it is expected that technology for domestic sized hydrogen boilers could be used to meet light to medium commercial heating demands, either using a cascade of domestic sized boilers (< 30 kW) or a scaled-up commercial variant (30-70 kW). However, it is acknowledged that the challenges involved in designing boilers to meet safety, emissions and efficiency targets become greater as the appliance output rating increases.

Heavy-duty commercial boilers over 400kW in rated input, which are generally non-condensing with pressure jet type burners and outside the scope of the Ecodesign Directive, are estimated to account for approximately 3% (15,000) of the installed base of commercial boilers.

Technical Challenges and Appliance Development

The technical challenges to developing hydrogen appliances for use in the commercial sector are deemed to be surmountable and should largely be addressed by domestic appliance development programs already underway and existing hydrogen boiler applications in the industrial sector. The proof of concept with domestic appliances that successfully demonstrate stable hydrogen combustion, reliable flame detection and safety systems, and achieve efficiency and emissions targets with suitable materials of construction proven to maintain gas tightness, should support the view that it is technically feasible to develop commercial appliances which run on 100% hydrogen, as many of the components are shared (or are scaled up versions) and sourced from a relatively small pool of manufacturers/suppliers.

The key differences in the technical challenges faced by manufacturers in the development of appliances for the commercial sector, compared to the domestic and industrial sectors, are:

- increased effort, in terms of design and technical complexity, to achieve functional safety of the appliance (i.e. consequences of delayed ignition explosions could be much greater than domestic);
- larger variety of burners must be developed to safely and efficiently deliver the wide range of heat inputs required by commercial appliances (i.e. 5 kW commercial hob burner through to 1 MW pressure jet burner for shell boiler);
- more complex design and optimisation for appliance heat transfer, efficiency and emissions (e.g. non-linear increase in combustion chamber volumes when scaling up from domestic; desire to achieve same footprint as current natural gas appliances when scaling down from industrial appliances with additional low NO_x technology/abatement);
- ‘bake quality’ and cooking time are more critical as meals are the commercial product and livelihood of most catering end users;
- cascading of multiple smaller units to meet large peak heating demands with high turn-down ratios; and
- appliance installation considerations such as hazardous area rating, certified equipment specification, fresh air supply, flue arrangements, plant room gas detection and associated safety shutdown.

It is acknowledged that many of these items are not ‘barriers’, rather they are areas where significant effort and investment is likely to be required in the research and development phases.

The development of ‘hydrogen ready’ appliances, which are designed to work optimally on 100% hydrogen following some minor amendments, but can also function safely on natural gas prior to this, has been identified by manufacturers as the key for successful transition to using 100% hydrogen for heat.

Wider Challenges

The diversity of commercial buildings (see Section 4.1.2 for detailed definition) is much greater than for the domestic sector in terms of their physical size and heat demand. This diversity, coupled with the low fuel consumption relative to the domestic and transportation sectors (in terms of overall consumption) and industrial sector (in terms of energy intensity), has meant that while decarbonisation continues to grow in profile, the commercial sector has received much less attention than other sectors to date.

No significant development of commercial appliances has been identified to date, and this reflects both the relatively small market for commercial appliances in the UK, both in comparison to the domestic appliance market in the UK and more broadly to the worldwide commercial appliance market (i.e. no ‘pull’) and a perceived absence of a clear policy or vision for a hydrogen economy in the near future (i.e. no ‘push’).

While it is deemed technically feasible to develop commercial appliances to function safely and effectively with 100% hydrogen, the challenge to do so cost effectively is considered to be far greater.

Securing User Acceptability

Knowledge of hydrogen and its potential to replace natural gas as a fuel for heating is generally low within the commercial end user population. Currently there is a perception among some end users that hydrogen may be unsafe for commercial use. However, there is also an acceptance from some end users that the safety case for hydrogen would need to be approved before the decision supporting mass conversion is made.

Costs and Timelines for Sector Conversion

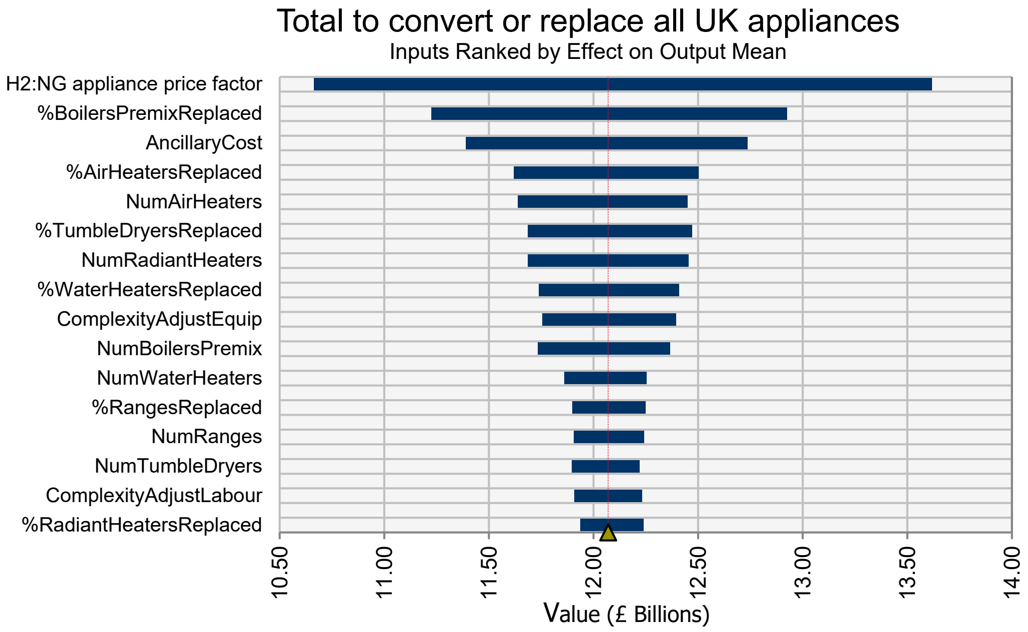
The cost to convert commercial sector appliances from natural gas to 100% hydrogen is estimated to be £10.1 - £14.3 billion. This estimate is based on a Monte Carlo analysis of the ‘per unit’ conversion/replacement cost multiplied by the installed base for the appliances studied. No account is made for significant changes to overall energy demand and technology prevalence between now and the start of conversion.

The base case estimate reflects the feedback from appliance manufacturers at the time the analysis was undertaken (August 2019). However, this is a rapidly developing field and recent comments by manufacturers suggest the cost of hydrogen ready appliances might reduce further relative to a gas boiler. To reflect this, a sensitivity analysis was undertaken to investigate the potential impact on conversion costs if hydrogen ready appliances are less expensive than the view indicated by manufacturers during the study. This sensitivity resulted in a cost to convert commercial sector appliances of between £8.9 and £11.2 billion.

Wall hung and floor standing pre-mix boilers (boilers which utilise burners that blend air and natural gas to within flammable limits prior to the point of ignition), with rated outputs of 400 kW or less, are predicted to contribute the most to the overall conversion cost, both in magnitude (due to the relatively large installed base) and uncertainty (due to the current lack of understanding of what proportion of boilers could be converted rather than requiring replacement with a new hydrogen appliance). The base case model assumes 50% of boilers are replaced and 50% are hydrogen ready appliances which are converted. Currently installed stock (non-hydrogen-ready) is not considered technically or economically feasible to convert.

The Monte Carlo analysis was performed on key input variables to determine the sensitivity of the cost estimate to uncertainty in the inputs. The main contributors to uncertainty in the overall cost estimate are:

- The cost of a new 100% hydrogen appliance (relative to current natural gas appliance).
- The percentage of pre-mix boilers which can be converted rather than require replacement with a new 100% hydrogen appliance. The base-case model assumes non-hydrogen-ready appliances cannot be converted, so must be replaced.
- Ancillary costs incurred during the conversion process (e.g. pipework replacement).


Total to convert or replace all UK appliances
Inputs Ranked by Effect on Output Mean
H2:NG appliance price factor
%BoilersPremixReplaced
AncillaryCost
%AirHeatersReplaced
NumAirHeaters
%TumbleDryersReplaced
NumRadiantHeaters
%WaterHeatersReplaced
ComplexityAdjustEquip
NumBoilersPremix
NumWaterHeaters
%RangesReplaced
NumRanges
NumTumbleDryers
ComplexityAdjustLabour
%RadiantHeatersReplaced
10.50
11.00
11.50
12.00
12.50
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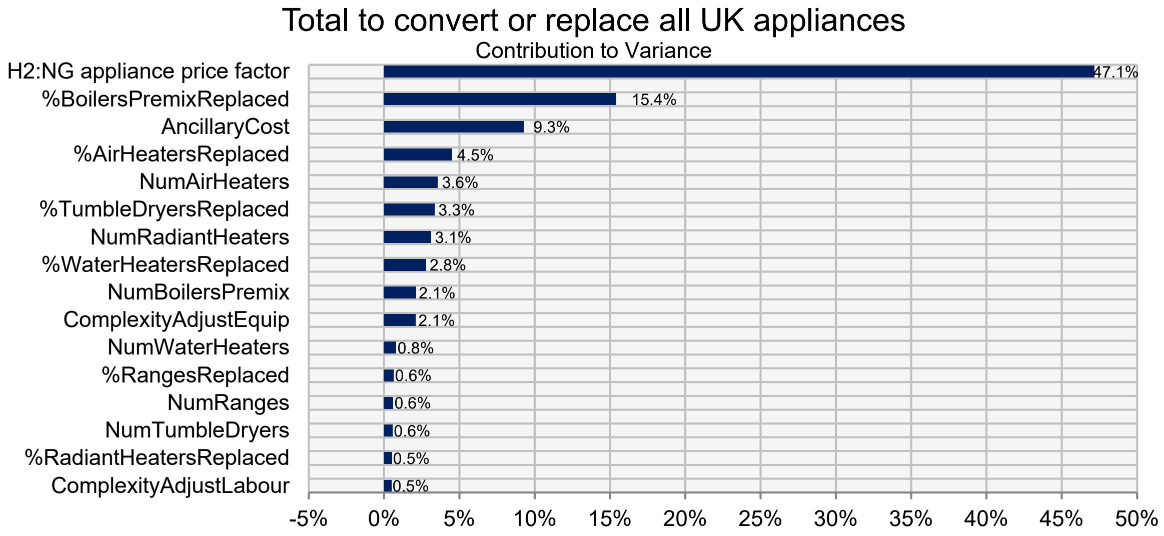
Value (£ Billions)


Total to convert or replace all UK appliances
Contribution to Variance
H2:NG appliance price factor
47.1%
%BoilersPremixReplaced
15.4%
AncillaryCost
9.3%
%AirHeatersReplaced
4.5%
NumAirHeaters
3.6%
%TumbleDryersReplaced
3.3%
NumRadiantHeaters
3.1%
%WaterHeatersReplaced
2.8%
NumBoilersPremix
2.1%
ComplexityAdjustEquip
2.1%
NumWaterHeaters
0.8%
%RangesReplaced
0.6%
NumRanges
0.6%
NumTumbleDryers
0.6%
%RadiantHeatersReplaced
0.5%
ComplexityAdjustLabour
0.5%
-5%
0%
5%
10%
15%
20%
25%
30%
35%
40%
45%
50%

8.2 Recommendations

8.2.1 Main Recommendations for Hy4Heat and Government

As a result of the market research conducted for Work Package 5, a set of recommendations has been proposed to help the Hy4Heat team and BEIS prepare for potential community trials with hydrogen fuelled commercial appliances. The recommendations are grouped into three key themes.

1. **Improved Data Quality**
    1.1. Many of the assumptions used in the cost model are based on a small set of data points. This was due largely to limited engagement responses for many of the key stakeholders in the commercial sector, many of whom identified the lack of a business case for investing in hydrogen development for not participating further. A further tranche of stakeholders would not engage with the WP5 team – it is considered that this decision related to a lack in business relevance of hydrogen transition to the majority of those unwilling to engage in dialogue. It is recommended that commercial sector stakeholders are mapped according to their influence and interest in hydrogen transition, and to develop a proactive strategy to increase the level of interest for key stakeholders such as trade bodies, facilities management companies, national retailers, etc.

    1.2. The cost model includes some significant assumptions to account for the uncertainty in the input data. It is recommended that BEIS and the Hy4Heat team review the assumptions with manufacturers taking part in WP5b to refine the overall cost estimate, focussing on those assumptions which make the greatest contribution to actual cost and uncertainty in the cost estimate.

    1.3. Through engagement with the relevant trade association, FEA, and its members, this study found that there are no industry aggregated statistics for commercial catering appliances installed in the UK. The level of confidence in commercial catering appliance counts presented in this report and their distribution across the subsectors is therefore low. It was found that detailed knowledge of the make-up of the commercial catering market in terms of food service outlets and the appliances installed within those kitchens is collectively held by a small number of private consultancies and industry experts. It is recommended to engage with FEA to commission a detailed study of the commercial catering sector to improve the estimate of installed gas appliances in the UK.

    1.4. The level of engagement with private sector stakeholders was generally low, and as such private sector appliance populations and their distributions across the subsectors and end use settings is largely unknown, most notably for warm air and radiant heaters. It is recommended that BEIS and the Hy4Heat team engage further with relevant private sector stakeholders, such as large end users and facilities management companies, to provide them with more detailed information relating to developments in the hydrogen economy and potential policy mechanisms, in order to improve the value proposition for them providing data on installed appliances.

2. **Appliance development**
    2.1. Engagement with commercial appliance and component manufacturers and others within the appliance development and supply chain was often limited to general discussions due to the potential for intellectual property rights infringements. Step changes in industry, such as the potential conversion of the national gas grid from natural gas to hydrogen, are often more successful when the industry comes together to work towards a common goal. It is recommended that BEIS and Hy4Heat work closely with the relevant trade bodies to promote knowledge sharing within and between appliance and component manufacturers to ensure that economies of scale are maximised for early development of hydrogen appliances which can be cost competitive.

3. Hydrogen awareness

3.1. Commercial end users are generally unaware of the potential for hydrogen to replace natural gas as a fuel for heating, and are already replacing existing fossil fuel heating appliances with other renewable/low carbon options. It is recommended that a campaign of public engagement is commissioned, to educate commercial end users and those responsible for commercial space heating selection on hydrogen safety, the potential benefits of using hydrogen as a fuel for heating, and current developments in the establishment of a hydrogen economy.

4. Community Trial

4.1. The following commercial appliances are recommended for inclusion in any potential community trial. The appliances have been selected based on a set of criteria including installed base, contribution to annual gas consumption, being unique to the commercial sector.

- Boiler (<70 kW) installed in cascade arrangement of two or more units
- Warm air heater
- Radiant tube and/or radiant plaque heater
- Commercial catering appliances
  - Range
  - Fryer
  - Grill
  - Chargrill
  - Combination Oven

4.2. The choice of site for a small community trial should consider the variety of premises which are present in the UK commercial sector. If a single site is to be selected, the site should have the following buildings to prove the key heating requirements of the commercial sector:

- Large indoor space where wet central heating is required (e.g. offices)
- Large indoor space where radiant heating is required (e.g. gymnasium)
- Large indoor space where warm air heating is required (e.g. workshop)
- On-site kitchen providing large number of meals per day

Using the above criteria, a single site which is likely to fulfil all of the requirements includes a school, university, prison, hospital and fire station. Alternatively, a small village or commercial centre could be selected, thereby allowing for more end use settings to be included. A study should be commissioned, or nomination process commenced, to identify the most suitable location which covers the most representative spread of commercial premises.

8.2.2 Knowledge Gaps

- Relative distribution of boilers, water heaters, warm air heaters and radiant heaters across the commercial and industrial subsectors and end use settings.
- Low confidence in total installed base and relative distribution of catering appliances across the commercial subsectors and end use settings.
- Commercial appliance counts and distributions within private sector end uses
- Appliance longevity; heat transfer effects due to changes in flame profile (potential flame impingement, lack of radiant heat); possible changes to flame monitoring and control systems;

impacts to appliance footprint to meet same outputs as natural gas equivalent appliance; ability to meet emissions and efficiency targets concurrently; which appliances could be economically converted and which could not; and specific flueing requirements.

- Bake quality and taste of bread products baked in appliances using 100% hydrogen.

8.2.3 Supplementary Recommendations from WP5

1. The relative distribution of boilers, water heaters, warm air and radiant heaters across the Commercial and Industrial sub-sectors and end uses is not well defined. Further engagement with key stakeholders in the commercial heating appliance industry, e.g. building service engineers, is required to better understand the relative distribution of commercial heating appliances within the sub-sectors and end uses.
2. There is low confidence in total installed base and relative distribution of catering appliances across the Commercial sub-sectors and end uses. It is recommended to engage FEA to commission a targeted study to more accurately estimate the number of gas fired commercial catering appliances installed in commercial kitchens in the UK.
3. Bakery ovens are a known gap in the study to date. It is recommended that engagement with stakeholders in the Bakery sector is made, and that as part of the appliance demonstration trials, a variety of bread products are baked and subjected to taste tests to highlight any major differences with natural gas baked products.
4. Commercial appliance counts and distributions within private sector end uses is largely unknown. It is recommend that further engagement with FM companies is attempted to obtain detailed appliance data for private sector users.
5. It is recommended that a knowledge-sharing event is held for appliance manufacturers to understand the current research programs and knowledge base for working with 100% hydrogen to facilitate further appliance development.
6. Feedback from industry is that natural gas warm air heaters are already having difficulty meeting the next round of ErP targets (2016/2281 from 1st January 2021) for NO_x emissions and efficiency concurrently. However, manufacturers working on Hy4Heat domestic appliances have preliminary findings that NO_x emissions were lower than natural gas equivalents, while maintaining efficiency. Further evidence is required on commercial scale air heaters to indicate whether well-designed appliances could meet emissions and efficiency limits. Hy4Heat WP5B has funded commercial scale air heater development which will address this evidence gap.
7. As part of the future demonstration trials, consider implementing a taste test for foods cooked using hydrogen appliances versus natural gas and electric.
8. The following key knowledge gaps relevant to appliance development and functionality should be investigated and closed out: appliance longevity; heat transfer effects due to changes in flame profile (potential flame impingement, lack of radiant heat); possible changes to flame monitoring and control systems; impacts to appliance footprint to meet same outputs as natural gas equivalent appliance; ability to meet emissions and efficiency targets concurrently; which appliances could be economically converted and which could not; and specific flueing requirements.
9. The process for converting commercial end users must be considerate of the unique demands for and criticality of supply continuity of heat within each Commercial end use type, as well as any other conversion constraints such as geography.
10. BEIS may wish to undertake cost-benefit analysis in order to understand the most cost effective means of government support for these early stage costs. The potential economic advantages (for example GVA and job creation) of R&D support for manufacturers could be

compared under a range of options, from limited support of a small fraction of the investment requirements to more significant government support of a higher percentage.

11. The appliances with the most information made available by manufacturers were boilers, air heaters and radiant heaters, while the appliances with the least information available were rotisseries and tumble dryers. To some extent these gaps reflect the fact that manufacturers may simply not know the answers to the questions posed. Further analysis of the appliances associated with the most uncertainty is recommended in order to refine the assumptions used in the analysis.
12. The cost of a new appliance which can run on 100% hydrogen when compared with an existing natural gas appliance was a key uncertainty associated with the analysis. A base case factor was applied based on feedback from manufacturers and publicly available research. Monte Carlo analysis suggests this is a key influence on the cost estimates, therefore it is recommended that further research is undertaken in this area.
13. The scale and timing of development of “hydrogen ready” appliances is a key unknown. If wide scale rollout of these appliances was achieved, for example in catering appliances which have a relatively low lifetime compared with boilers, then the conversion costs would be expected to be significantly lower than conversion of non-hydrogen ready appliances. Further research in this area is recommended, for example BEIS may wish to consider how the UK conversion costs may reduce under a range of scenarios in which differing levels of early stage support and policy signals are used to support the development of hydrogen ready appliances.
14. The survey and ancillary works costs used in the modelling of conversion and replacement were based on publicly available research in order to establish per unit values. It is recommended that further research is undertaken in order to refine these costs, for example through community demonstration trial in order to establish for example cost savings arising from economies of scale and conversion/replacement of multiple units in the same premises. Monte Carlo analysis suggests that ancillary works costs in particular are a key influence on the cost estimates, and it is notable that estimates for this cost varied significantly in publicly available research .
15. The model methodology used to calculate equipment and labour costs for conversion is based on the complexity of the appliance and the appliance value. Similarly, the labour cost for replacement is based on publicly available research. There were very limited data points to determine these values and so they follow a fairly linear relationship with the equipment value, it is recommended that manufacturers provide further information in order to refine these estimates further.
16. Replacement or conversion of all units of the 17 selected appliances installed in the UK is estimated to take place from 2028 in a phased approach. This analysis is based on high-level assumptions around government support and the creation of a hydrogen market. Policy makers may wish to consider a number of different options for supporting the development of the hydrogen market and conversion of the UK gas grid, and the policy signals required to achieve the target timelines.

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Preparatory Studies for Ecodesign Requirements of EuPs (III); ENER Lot 21 – Central heating products that use hot air to distribute heat; Task 2: Economic and Market Analysis; European Commission, DG ENER, July 2012	https://www.eceee.org/ecodesign/products/lot21-central-heating-products/
Preparatory Studies for Ecodesign Requirements of EuPs (III); ENER Lot 22 – Domestic and commercial ovens (electric, gas, microwave), including when incorporated in cookers; Task 2: Economic and Market Analysis; European Commission, DG ENER, August 2011	https://www.eceee.org/ecodesign/products/lot22-23-kitchen/
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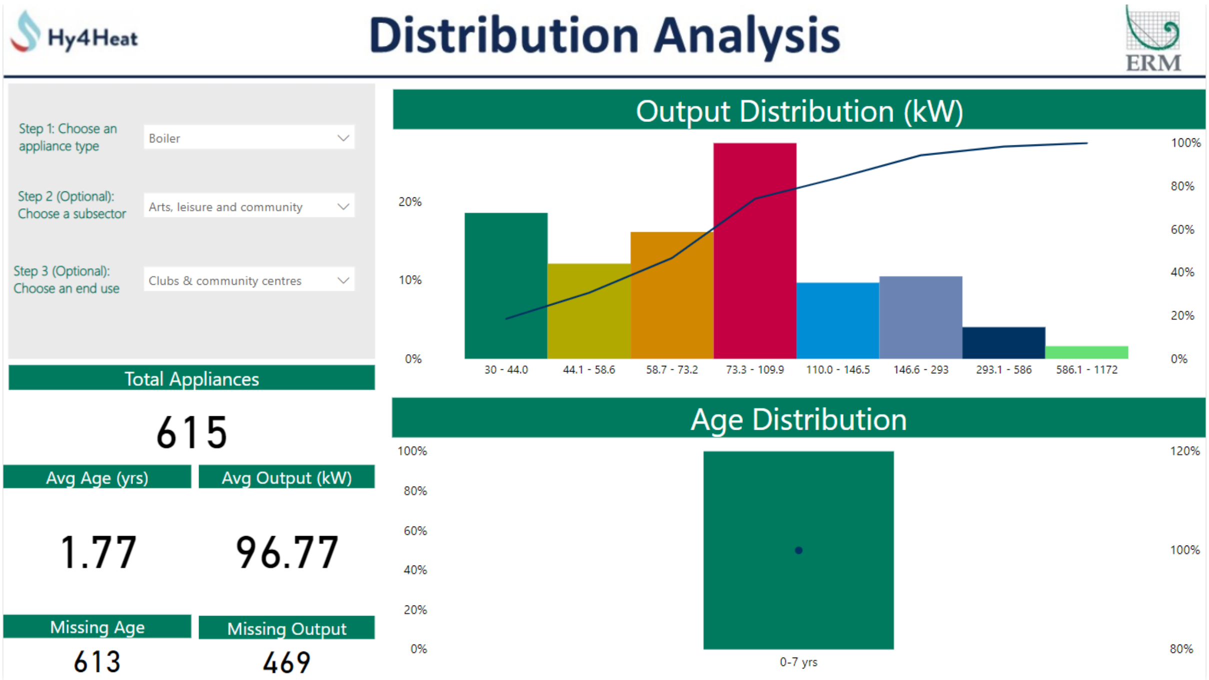
10. APPENDICES

10.1 Appendix A: FOI Appliance Dashboards



Distribution Analysis

Step 1: Choose an appliance type: Boiler

Step 2 (Optional): Choose a subsector: Arts, leisure and community

Step 3 (Optional): Choose an end use: Clubs & community centres

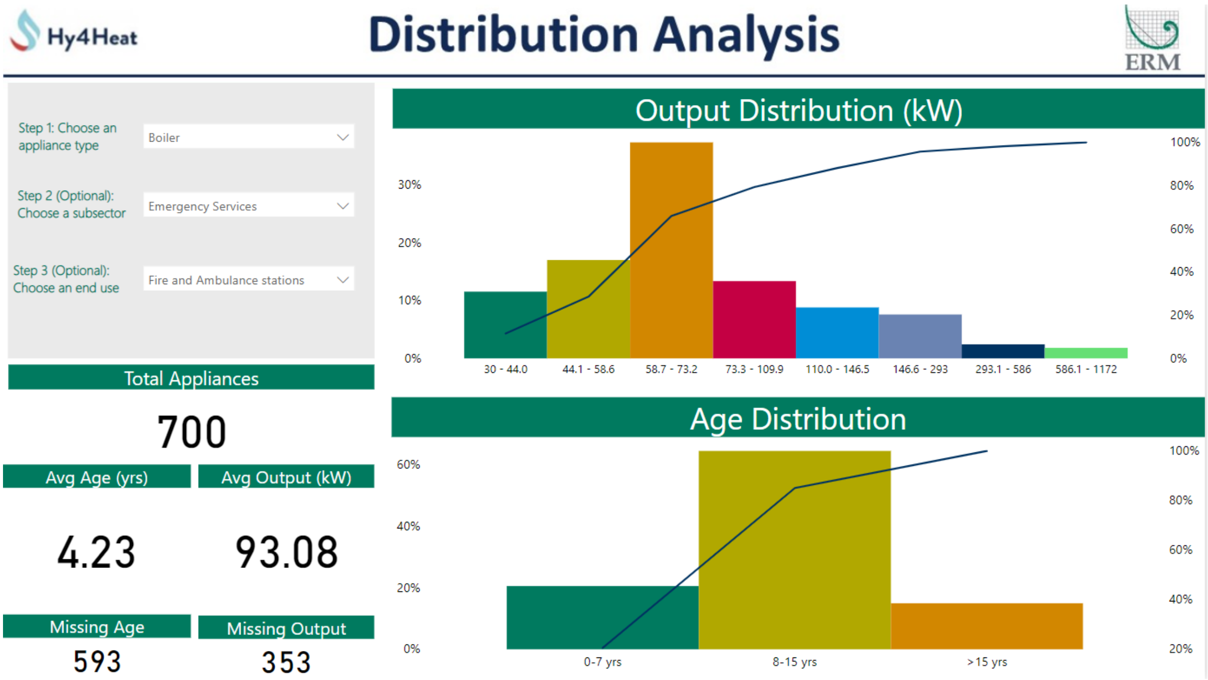
Total Appliances: 615

Avg Age (yrs): 1.77

Avg Output (kW): 96.77

Missing Age: 613

Missing Output: 469



Distribution Analysis

Step 1: Choose an appliance type: Boiler

Step 2 (Optional): Choose a subsector: Emergency Services

Step 3 (Optional): Choose an end use: Fire and Ambulance stations

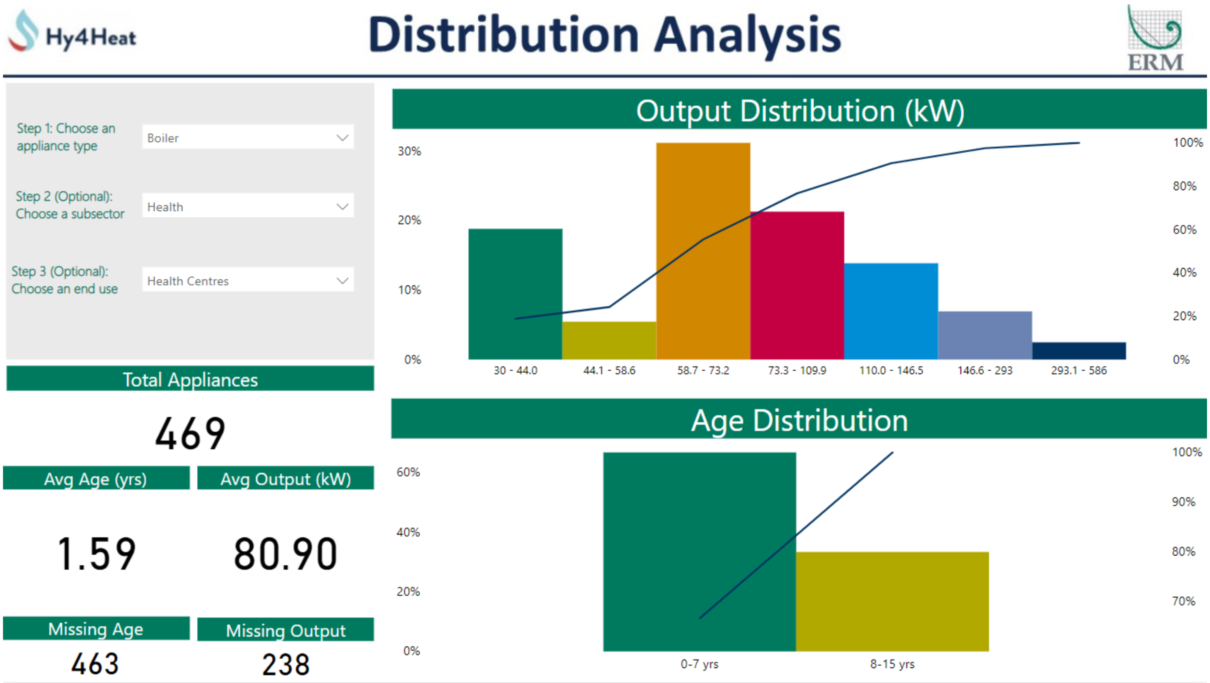
Total Appliances: 700

Avg Age (yrs): 4.23

Avg Output (kW): 93.08

Missing Age: 593

Missing Output: 353



Distribution Analysis

Step 1: Choose an appliance type: Boiler

Step 2 (Optional): Choose a subsector: Health

Step 3 (Optional): Choose an end use: Health Centres

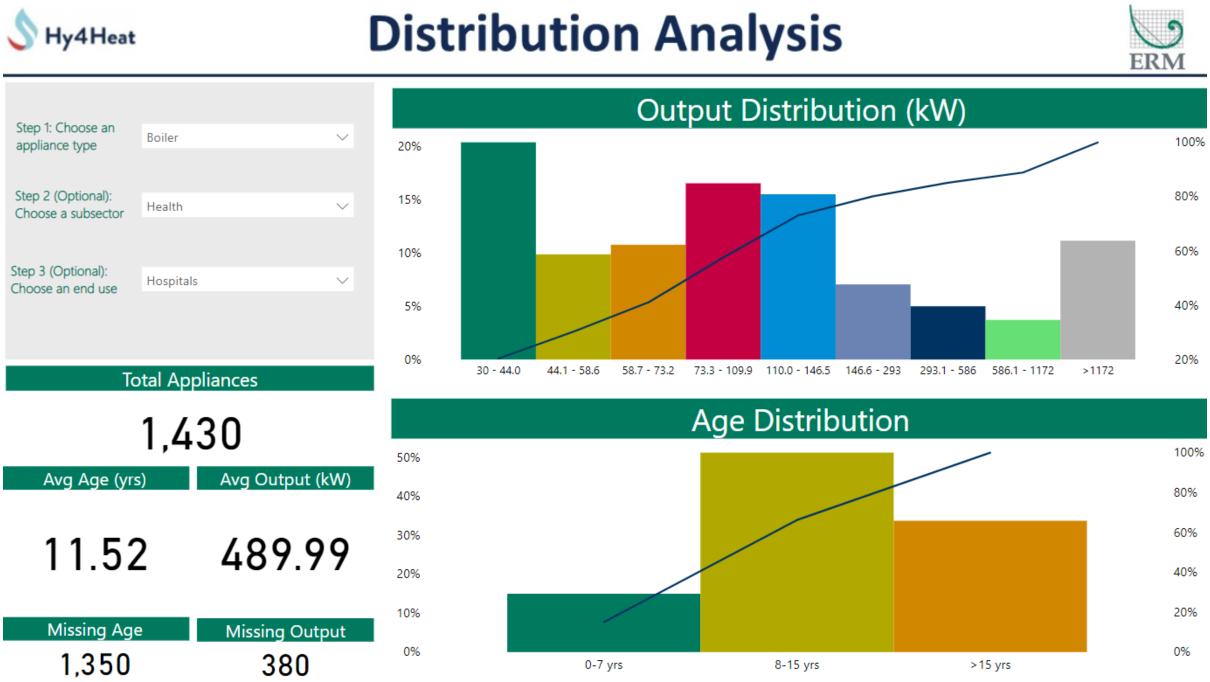
Total Appliances: 469

Avg Age (yrs): 1.59

Avg Output (kW): 80.90

Missing Age: 463

Missing Output: 238



Distribution Analysis

Step 1: Choose an appliance type: Boiler

Step 2 (Optional): Choose a subsector: Health

Step 3 (Optional): Choose an end use: Hospitals

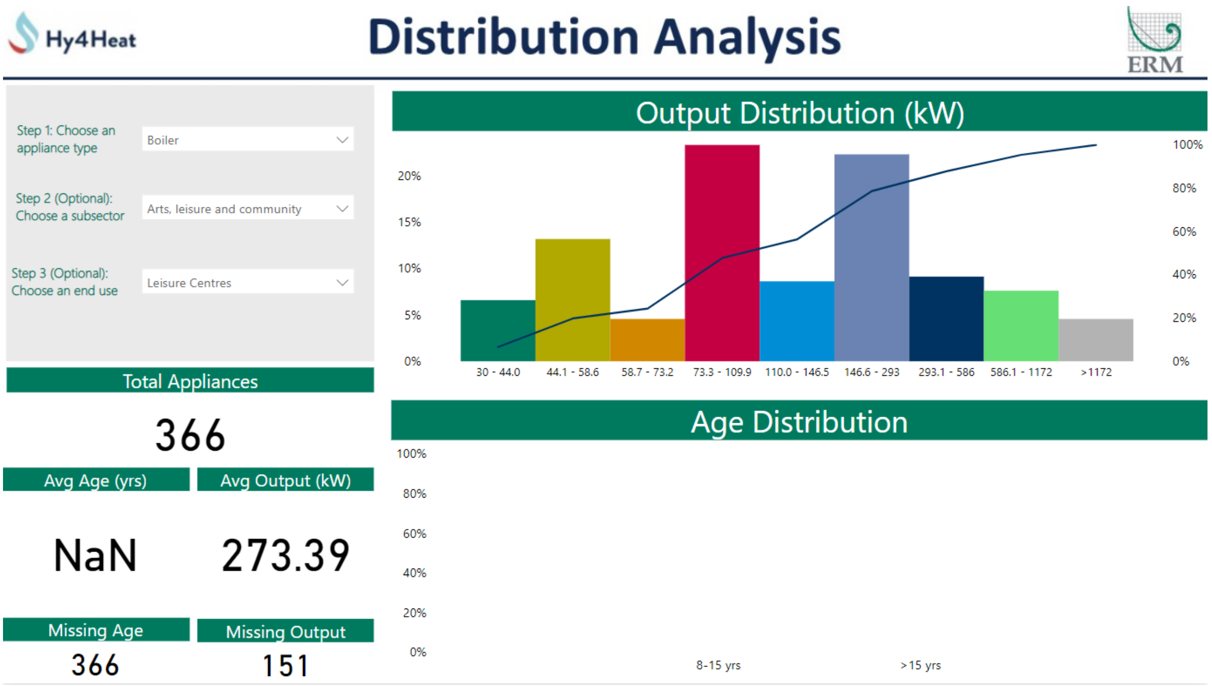
Total Appliances: 1,430

Avg Age (yrs): 11.52

Avg Output (kW): 489.99

Missing Age: 1,350

Missing Output: 380



Distribution Analysis

Step 1: Choose an appliance type: Boiler

Step 2 (Optional): Choose a subsector: Arts, leisure and community

Step 3 (Optional): Choose an end use: Leisure Centres

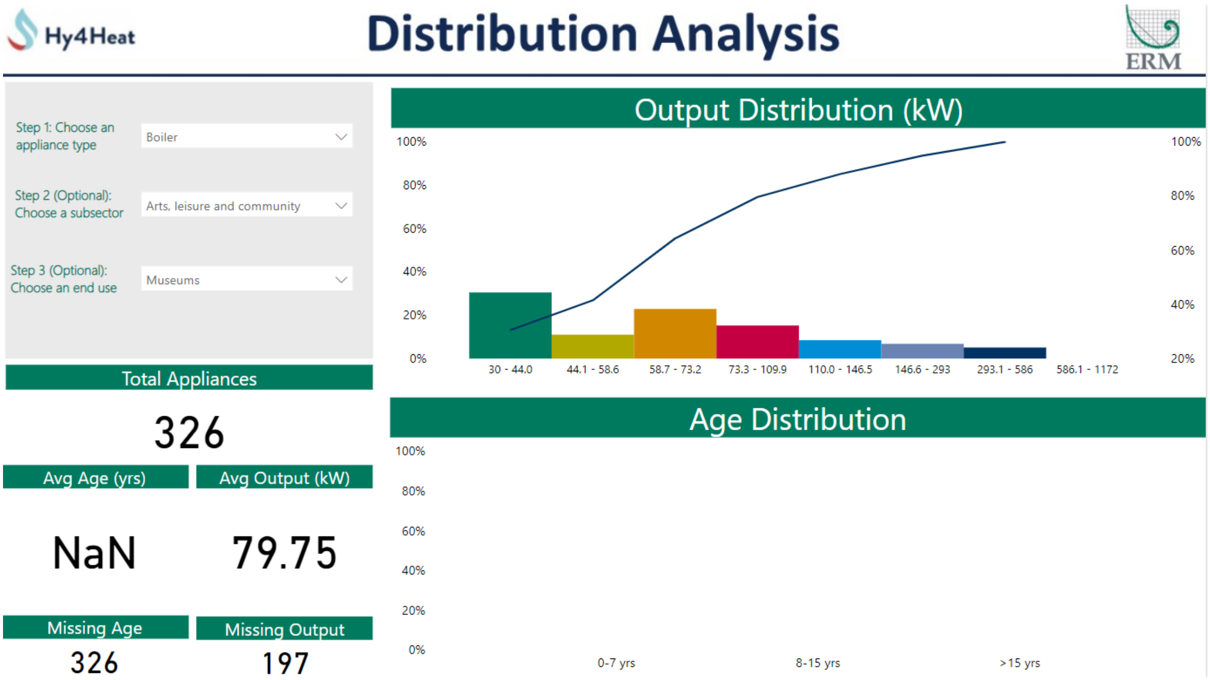
Total Appliances: 366

Avg Age (yrs): NaN

Avg Output (kW): 273.39

Missing Age: 366

Missing Output: 151



Distribution Analysis

Step 1: Choose an appliance type: Boiler

Step 2 (Optional): Choose a subsector: Arts, leisure and community

Step 3 (Optional): Choose an end use: Museums

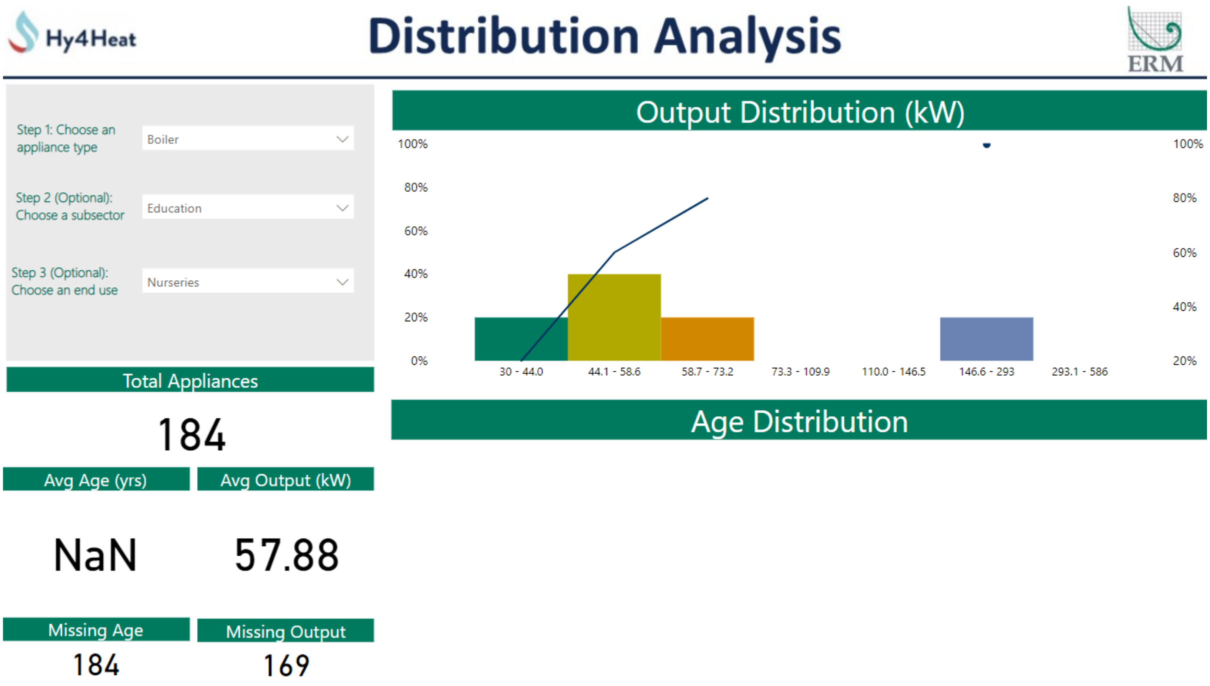
Total Appliances: 326

Avg Age (yrs): NaN

Avg Output (kW): 79.75

Missing Age: 326

Missing Output: 197



Distribution Analysis

Step 1: Choose an appliance type: Boiler

Step 2 (Optional): Choose a subsector: Education

Step 3 (Optional): Choose an end use: Nurseries

Output Distribution (kW)

Total Appliances: 184

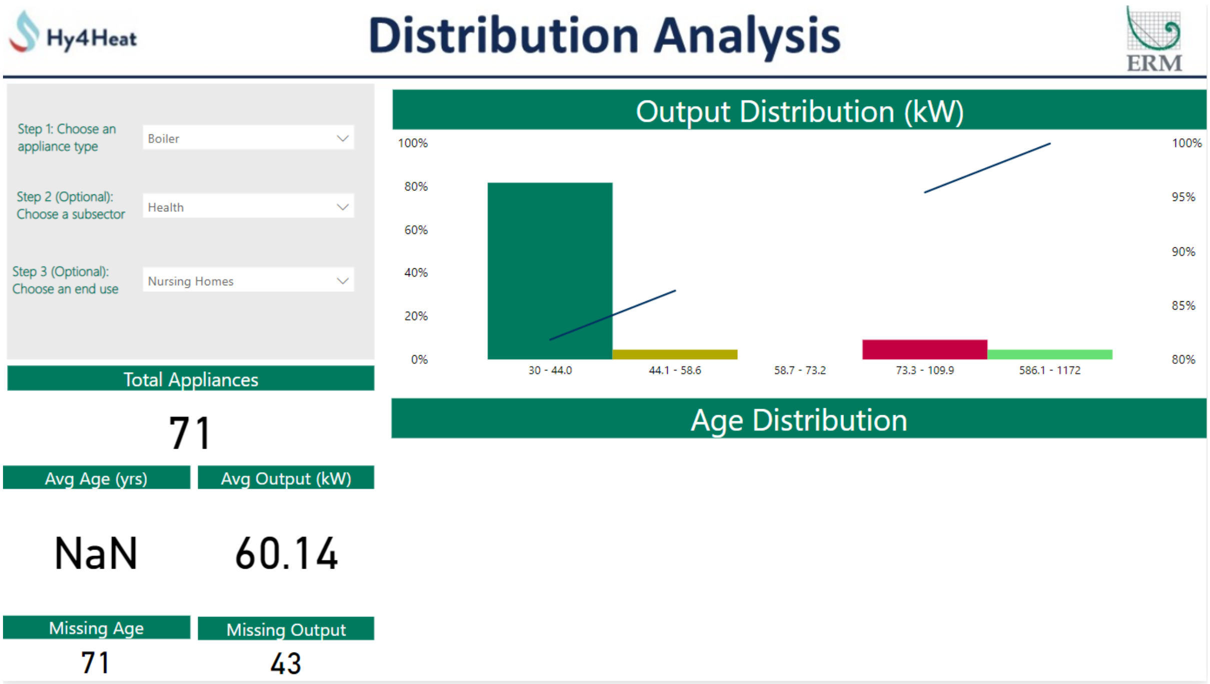
Age Distribution

Avg Age (yrs): NaN

Avg Output (kW): 57.88

Missing Age: 184

Missing Output: 169



Distribution Analysis

Step 1: Choose an appliance type: Boiler

Step 2 (Optional): Choose a subsector: Health

Step 3 (Optional): Choose an end use: Nursing Homes

Output Distribution (kW)

Total Appliances: 71

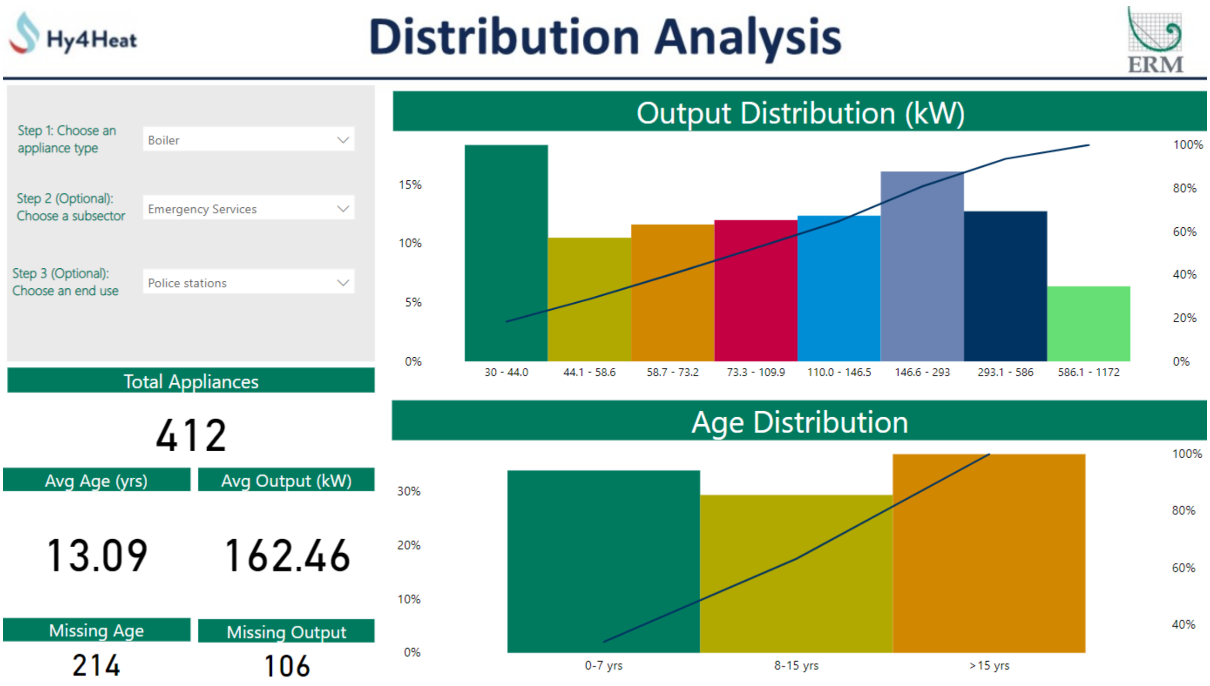
Age Distribution

Avg Age (yrs): NaN

Avg Output (kW): 60.14

Missing Age: 71

Missing Output: 43



Hy4Heat

Distribution Analysis

ERM

Step 1: Choose an appliance type: Boiler

Step 2 (Optional): Choose a subsector: Emergency Services

Step 3 (Optional): Choose an end use: Police stations

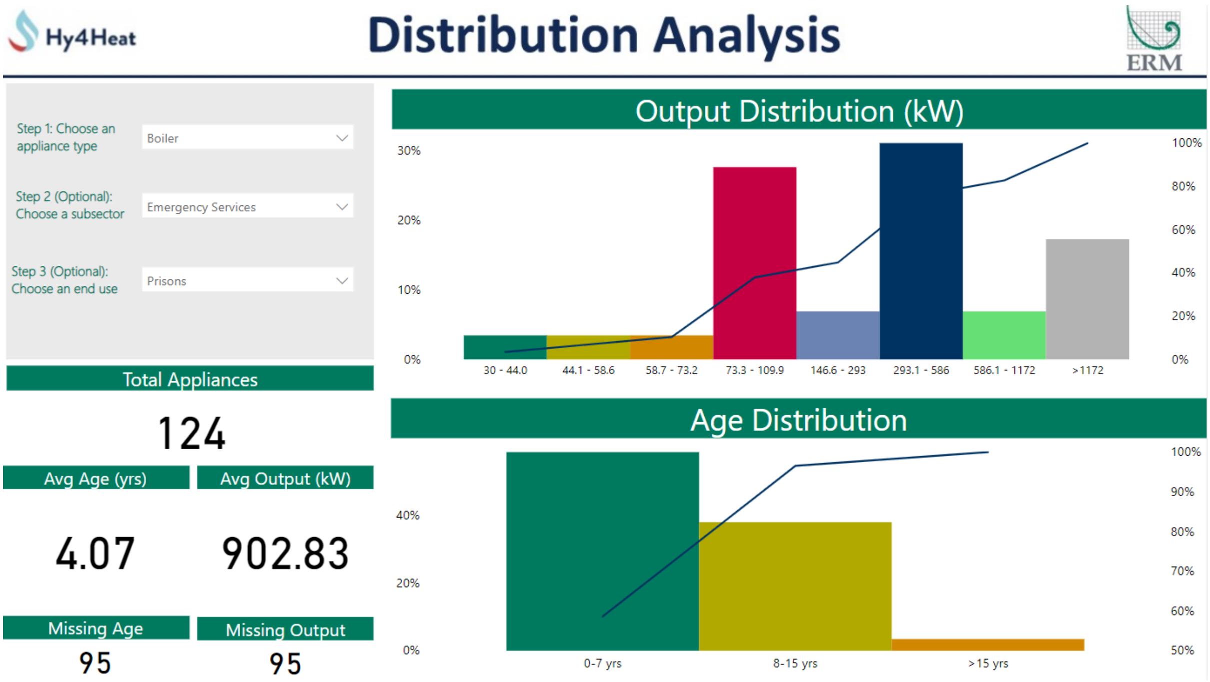
Total Appliances
412

Avg Age (yrs)
13.09

Avg Output (kW)
162.46

Missing Age
214

Missing Output
106



Hy4Heat

Distribution Analysis

ERM

Step 1: Choose an appliance type: Boiler

Step 2 (Optional): Choose a subsector: Emergency Services

Step 3 (Optional): Choose an end use: Prisons

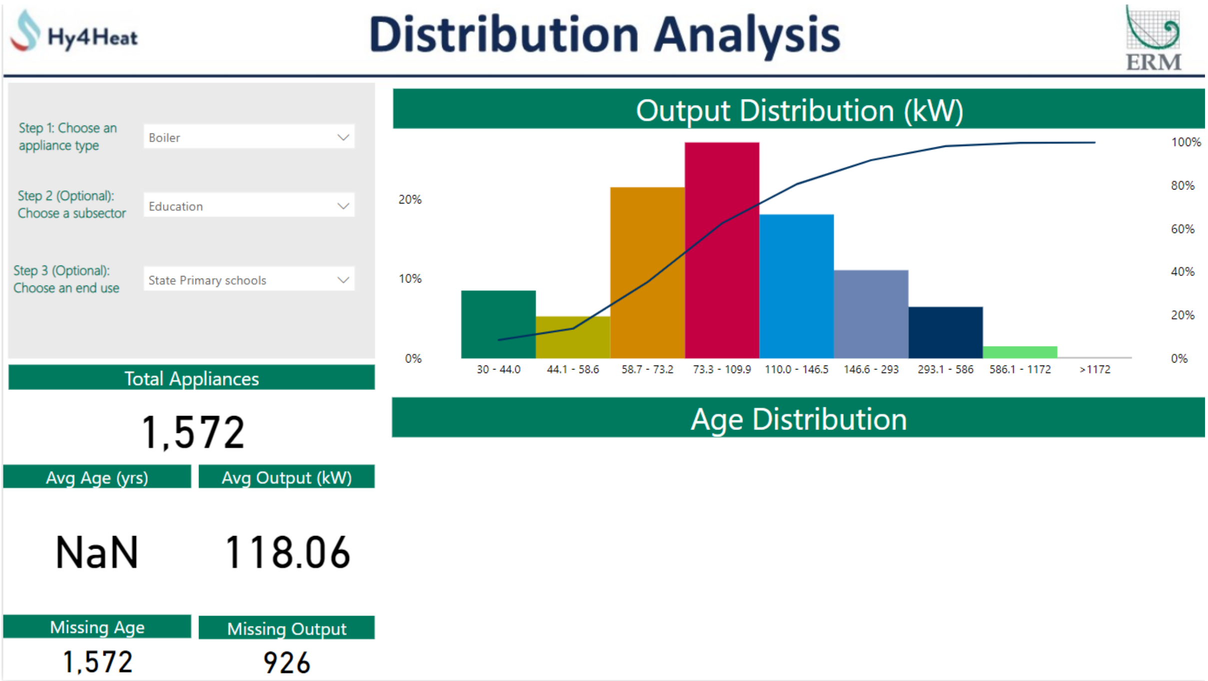
Total Appliances
124

Avg Age (yrs)
4.07

Avg Output (kW)
902.83

Missing Age
95

Missing Output
95



Hy4Heat

Distribution Analysis

ERM

Step 1: Choose an appliance type: Boiler

Step 2 (Optional): Choose a subsector: Education

Step 3 (Optional): Choose an end use: State Primary schools

Total Appliances: 1,572

Avg Age (yrs): NaN

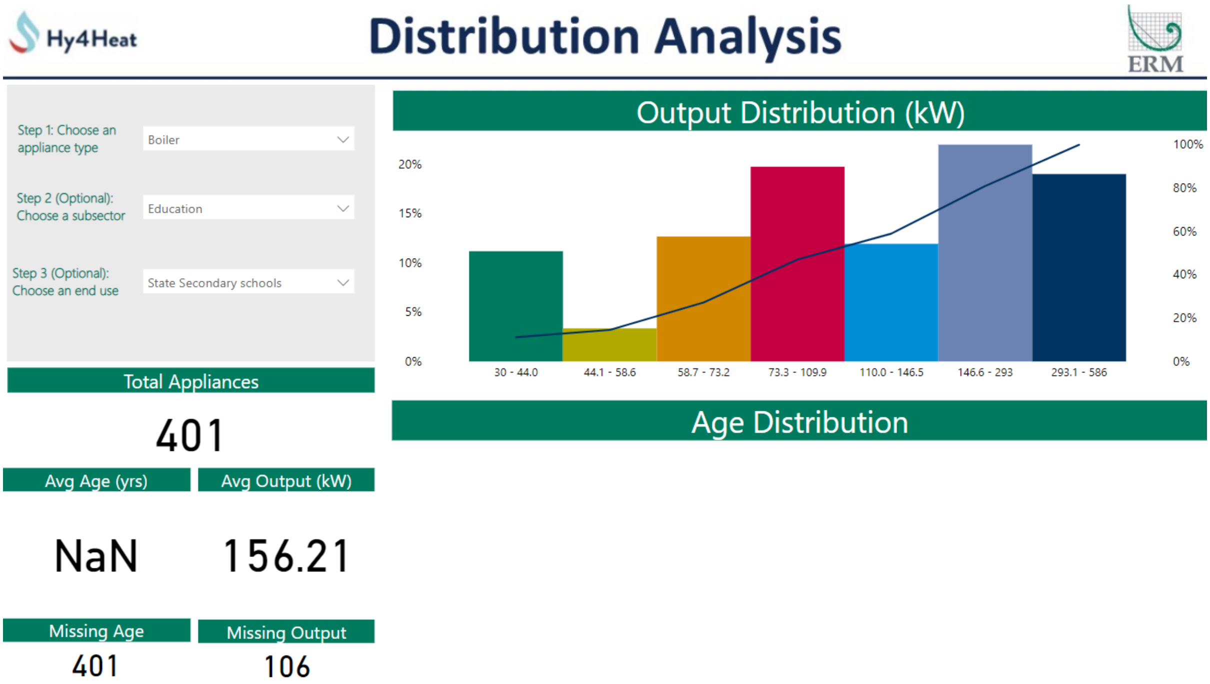
Avg Output (kW): 118.06

Missing Age: 1,572

Missing Output: 926

Output Distribution (kW)

Age Distribution



Hy4Heat

Distribution Analysis

ERM

Step 1: Choose an appliance type: Boiler

Step 2 (Optional): Choose a subsector: Education

Step 3 (Optional): Choose an end use: State Secondary schools

Total Appliances: 401

Avg Age (yrs): NaN

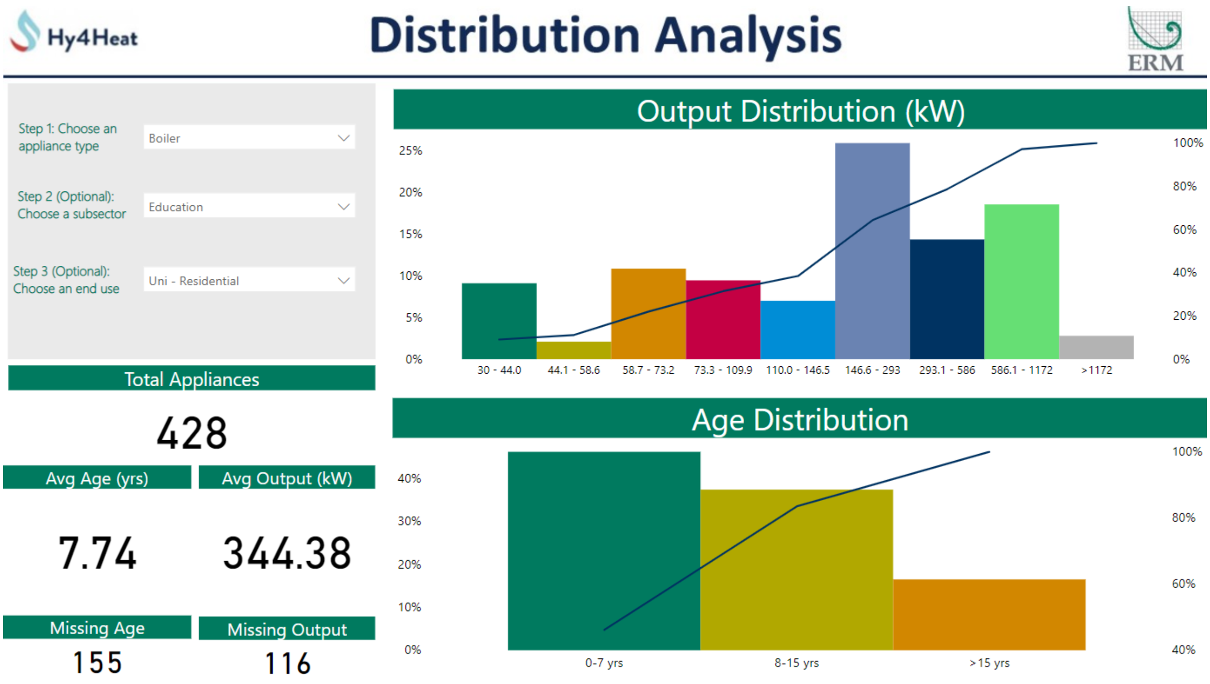
Avg Output (kW): 156.21

Missing Age: 401

Missing Output: 106

Output Distribution (kW)

Age Distribution



Distribution Analysis

Step 1: Choose an appliance type: Boiler

Step 2 (Optional): Choose a subsector: Education

Step 3 (Optional): Choose an end use: Uni - Residential

Total Appliances: 428

Avg Age (yrs): 7.74

Avg Output (kW): 344.38

Missing Age: 155

Missing Output: 116

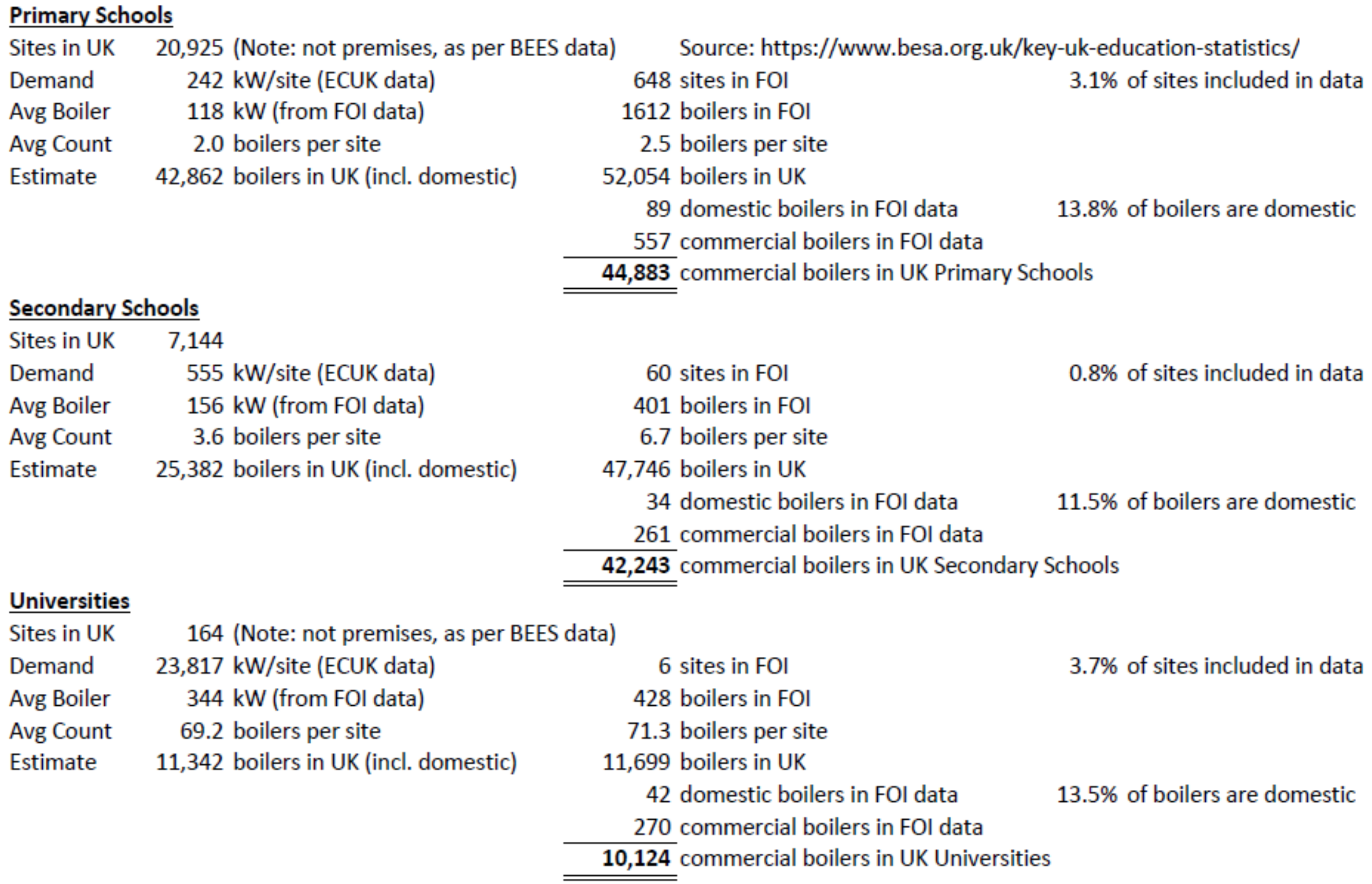
10.2 Appendix B: Top-Down Estimate Calculation

Input	Top 10 End Use
Assumption	Top 10% Sub-sector Usage
Calculation	

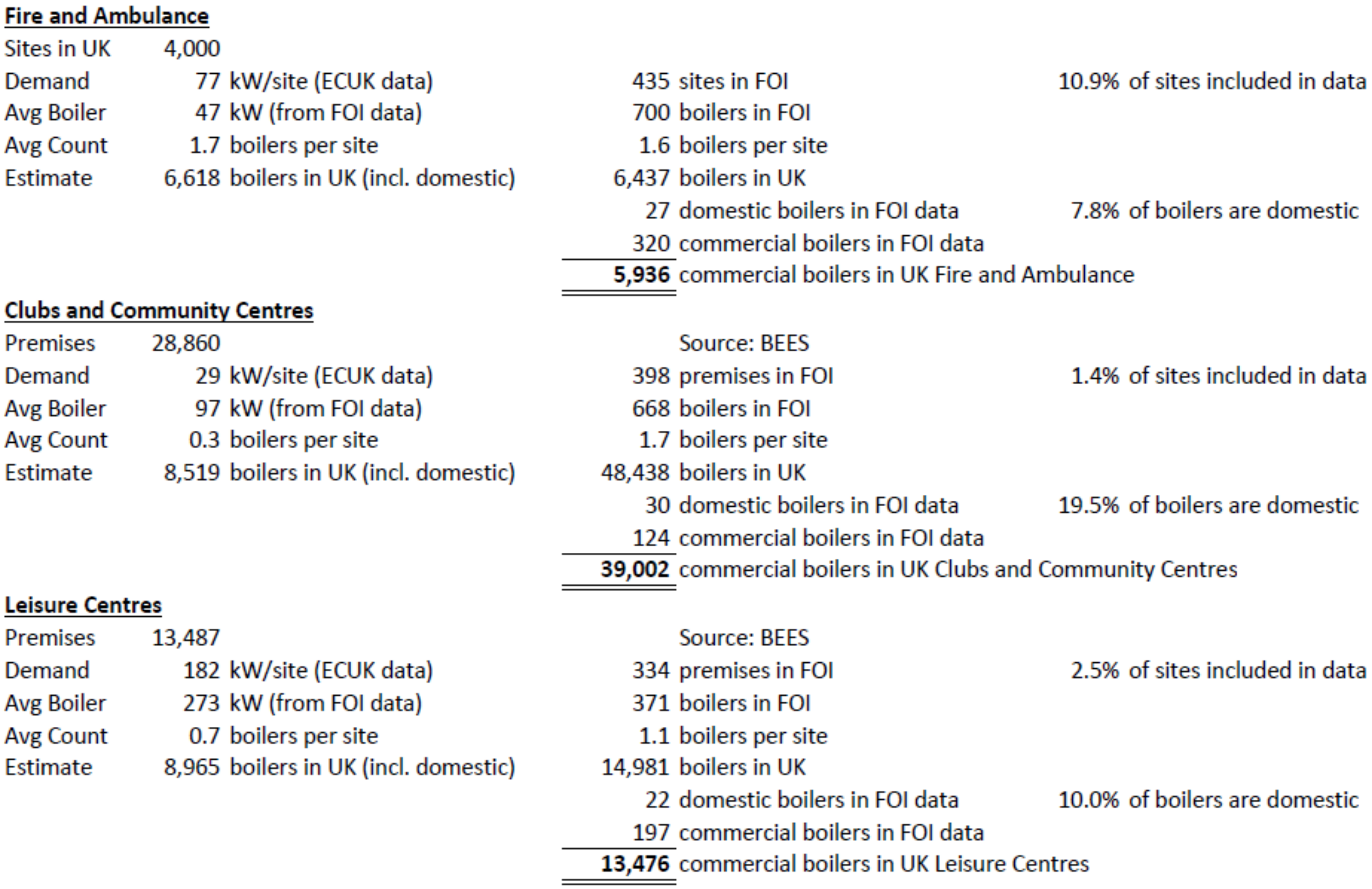
		ECUK Usage Data 1 ktoe = 11.63 GWh (Source: BEIS ECUK User Guide)							Commercial Property Population Data				
		Heating	Hot Water	Catering	Other	Total	Contribution	Public or Private Sector?	Number of premises	Footprint	Average Footprint	% footprint heated by gas	Footprint heated bt gas
		Natural Gas	Natural Gas	Natural Gas	Natural Gas	Natural Gas			Selected	Selected		(BEES)	
Subsector	End Use Setting	GWh	GWh	GWh	GWh	GWh	%		#	#	m2	%	m2
CA&L		8,184	339	647	2,871	12,045	12%		95,677	54,936,680	574	81%	44,498,711
	Clubs & community centres	1,571	92	219	-	1,881	2%	Mixed	28,860	7,222,222	250	81%	5,850,000
	Leisure Centres	1,800	211	-	2,871	4,882	5%	Mixed	13,487	4,444,444	330	81%	3,600,000
	Museums	138	5	7	-	154	0%	Mixed	2,220	238,889	108	81%	193,500
	Places of Worship	4,279	15	411	-	4,705	5%	Private	50,000	41,920,013	838	81%	33,955,211
	Theatres	397	16	10	-	423	0%	Private	1,110	1,111,111	1,001	81%	900,000
Education		12,912	1,949	821	215	15,897	15%		47,388	88,839,569	1,875	83%	73,736,842
	Nurseries	415	63	23	-	501	0%	Private	10,248	3,010,996	294	83%	2,499,127
	State Primary schools	4,952	712	179	63	5,905	6%	Public	20,925	30,778,000	1,471	83%	25,545,740
	State Secondary schools	3,880	704	310	62	4,956	5%	Public	7,144	29,687,289	4,156	83%	24,640,450
	Uni - Non-residential	3,011	214	257	90	3,572	3%	Private	3,158	19,197,854	6,079	83%	15,934,219
	Uni - Residential	655	257	51	-	962	1%	Private	5,913	6,165,430	1,043	83%	5,117,307
Emergency Services		4,382	553	22	-	4,957	5%		6,909	16,008,040	2,317	92%	14,727,397
	Fire and Ambulance stations	794	54	4	-	852	1%	Public	4,000	2,964,889	741	92%	2,727,698
	Law courts	221	6	1	-	229	0%	Public	565	1,261,992	2,234	92%	1,161,032
	Police stations	2,141	300	-	-	2,441	2%	Public	2,222	7,222,215	3,250	92%	6,644,438
	Prisons	1,226	192	17	-	1,435	1%	Public	122	4,558,945	37,368	92%	4,194,229
Health		11,251	3,694	655	3,482	19,082	18%		39,640	49,736,667	1,255	91%	45,260,367
	Health Centres	1,111	126	2	-	1,239	1%	Mixed	26,640	6,666,667	250	91%	6,066,667
	Hospitals	9,956	3,522	612	3,482	17,572	17%	Public	1,700	42,447,778	24,969	91%	38,627,478
	Nursing Homes	184	46	41	-	271	0%	Private	11,300	622,222	55	91%	566,222
Hospitality		4,122	1,212	3,872	105	9,309	9%		111,092	40,390,780	364	57%	23,022,745
	Cafes	53	32	404	-	489	0%	Private	13,439	1,818,147	135	57%	1,036,344
	Hotels	1,654	765	356	105	2,880	3%	Private	8,661	16,351,620	1,888	57%	9,320,423
	Pubs	2,115	281	1,552	-	3,948	4%	Private	54,582	16,172,453	296	57%	9,218,298
	Restaurants & takeaways	299	134	1,559	-	1,993	2%	Private	34,410	6,048,560	176	57%	3,447,679
Military		1,121	93	48	-	1,262	1%		25,713	12,797,227	498	60%	7,678,336
	Military civilian accommodation	94	27	7	-	129	0%	Public	6,817	638,631	94	60%	383,179
	Military offices	430	40	41	-	511	0%	Public	5,054	6,526,597	1,291	60%	3,915,958
	Military storage	597	25	-	-	622	1%	Public	13,843	5,631,999	407	60%	3,379,199
Offices		12,069	859	214	285	13,451	13%		90,048	131,181,080	1,457	62%	81,332,269
	Offices (private)	10,001	684	184	285	11,160	11%	Private	85,000	113,261,842	1,332	62%	70,222,342
	Offices (public)	2,067	175	31	-	2,291	2%	Public	5,048	17,919,238	3,550	62%	11,109,928
Retail		8,448	171	316	-	8,935	9%		531,686	114,996,757	216	39%	44,848,735
	Hairdressers	62	68	-	-	130	0%	Private	22,097	1,357,599	61	39%	529,464
	Large food shops	3,839	32	278	-	4,149	4%	Private	4,755	16,348,869	3,438	39%	6,376,059
	Large non-food shops	621	23	3	-	648	1%	Private	2,680	10,490,663	3,915	39%	4,091,359
	Retail Warehouse	1,238	3	-	-	1,240	1%	Private	9,598	15,219,599	1,586	39%	5,935,644
	Showrooms	974	27	8	-	1,009	1%	Private	8,861	4,546,089	513	39%	1,772,975
	Small shops	1,714	17	28	-	1,758	2%	Private	483,695	67,033,938	139	39%	26,143,236
Storage		6,023	226	57	-	6,306	6%		198,366	155,106,889	782	60%	93,064,133
	Cold Stores	1	24	-	-	25	0%	Private	369	2,232,728	6,059	60%	1,339,637
	Large Distribution Centres	1,227	52	50	-	1,329	1%	Private	1,198	29,501,148	24,632	60%	17,700,689
	Stores	363	8	-	-	371	0%	Private	79,956	12,366,652	155	60%	7,419,991
	Warehouses	4,432	142	7	-	4,581	4%	Private	116,844	111,006,361	950	60%	66,603,817
Industrial		12,100	180	120		12,400	12%		271,124	157,502,084	581	56%	88,201,167
	Factories	9,680	120	119		9,919	10%	Private	38,589	81,562,002	2,114	56%	45,674,721
	Workshops	2,420	60	1		2,481	2%	Private	232,535	75,940,082	327	56%	42,526,446
Total		80,613	9,274	6,771	6,958	103,644			1,417,643	767,502,084	541	63%	516,370,702
		78%	9%	7%	7%	100%							

		Top-Down Estimate: Space Heating								
		Adjusted Annual Consumption	Adjusted Intensity	Annual Usage Factor	Efficiency	Duty for Adjusted Annual Consumed	Wet/Dry split	FOI (or other) Average Boiler Size	Total Boilers	Air and Radiant Heaters
					%					
Subsector	End Use Setting	kWh/ premises	kWh/m2	%	80%	kW/ premises	%			
CA&L		142,661	248	29%	80%	71	85%		66,378	31,817
	Clubs & community centres	67,208	269	29%	80%	34	85%	97	19,870	3,506
	Leisure Centres	427,584	500	29%	80%	214	85%	273	9,285	14,013
	Museums	76,770	713	29%	80%	38	85%	133	1,528	270
	Places of Worship	105,649	126	29%	80%	53	85%	133	34,425	12,836
	Theatres	441,736	441	29%	80%	221	85%	133	1,269	1,191
Education		328,287	175	16%	80%	293	95%		76,802	22,741
	Nurseries	48,799	166	16%	80%	44	95%	58	8,081	425
	State Primary schools	285,102	194	16%	80%	255	95%	118	35,575	8,842
	State Secondary schools	654,314	157	16%	80%	584	95%	156	21,067	6,928
	Uni - Non-residential	1,148,784	189	16%	80%	1,026	95%	344	7,416	5,377
	Uni - Residential	133,367	128	16%	80%	119	95%	344	4,662	1,169
Emergency Services		689,405	298	40%	80%	246	85%		8,104	6,650
	Fire and Ambulance stations	215,724	291	40%	80%	77	81%	93	2,981	2,155
	Law courts	425,785	191	40%	80%	152	85%	133	505	474
	Police stations	1,047,441	322	40%	80%	374	88%	162	4,143	3,671
	Prisons	10,919,186	292	40%	80%	3,900	98%	903	475	350
Health		311,900	249	40%	80%	111	95%		42,104	11,325
	Health Centres	45,834	183	50%	80%	13	95%	81	23,030	1,212
	Hospitals	8,686,565	348	40%	80%	3,102	95%	490	9,305	9,599
	Nursing Homes	17,915	325	40%	80%	6	95%	60	9,769	514
Hospitality		65,090	179	29%	80%	33	50%		32,303	45,738
	Cafes	6,863	51	29%	80%	3	50%	133	3,830	3,830
	Hotels	335,122	178	29%	80%	168	50%	133	3,110	16,545
	Pubs	67,989	229	29%	80%	34	50%	133	15,556	15,556
	Restaurants & takeaways	15,263	87	29%	80%	8	50%	133	9,807	9,807
Military		72,692	146	23%	80%	45	50%		7,714	11,578
	Military civilian accommodation	23,090	246	23%	80%	14	50%	133	2,045	2,045
	Military offices	141,947	110	23%	80%	89	50%	133	1,516	5,380
	Military storage	71,833	177	23%	80%	45	50%	133	4,153	4,153
Offices		216,167	148	16%	80%	193	95%		58,832	21,551
	Offices (private)	189,781	142	16%	80%	169	95%	200	50,065	17,860
	Offices (public)	660,435	186	16%	80%	590	95%	200	8,767	3,691
Retail		40,740	188	29%	80%	20	66%		146,745	112,437
	Hairdressers	7,180	117	29%	80%	4	66%	133	5,688	2,930
	Large food shops	2,070,085	602	29%	80%	1,035	66%	133	9,525	26,106
	Large non-food shops	594,509	152	29%	80%	297	66%	133	1,542	4,225
	Retail Warehouse	330,636	209	29%	80%	165	66%	133	3,071	8,416
	Showrooms	281,812	549	29%	80%	141	66%	133	2,416	6,622
	Small shops	9,086	66	29%	80%	5	66%	133	124,503	64,138
Storage		50,608	65	29%	80%	25	20%		24,583	114,268
	Cold Stores	3,156	1	29%	80%	2	20%	133	44	177
	Large Distribution Centres	1,707,081	69	29%	80%	854	20%	133	922	19,628
	Stores	7,573	49	29%	80%	4	20%	133	9,595	38,379
	Warehouses	63,224	67	29%	80%	32	20%	133	14,021	56,085
Industrial		79,695	137	29%	80%	40	20%		33,322	259,056
	Factories	447,942	119	29%	80%	224	20%	133	7,278	154,880
	Workshops	18,584	32	29%	80%	9	20%	133	26,044	104,176
Total									496,886	637,161

10.3 Appendix C: Bottom-Up Estimate Calculations



Primary Schools						
Sites in UK	20,925	(Note: not premises, as per BEES data)		Source: https://www.besa.org.uk/key-uk-education-statistics/		
Demand	242	kW/site (ECUK data)	648	sites in FOI	3.1%	of sites included in data
Avg Boiler	118	kW (from FOI data)	1612	boilers in FOI		
Avg Count	2.0	boilers per site	2.5	boilers per site		
Estimate	42,862	boilers in UK (incl. domestic)	52,054	boilers in UK		
			89	domestic boilers in FOI data	13.8%	of boilers are domestic
			557	commercial boilers in FOI data		
			44,883	commercial boilers in UK Primary Schools		
Secondary Schools						
Sites in UK	7,144					
Demand	555	kW/site (ECUK data)	60	sites in FOI	0.8%	of sites included in data
Avg Boiler	156	kW (from FOI data)	401	boilers in FOI		
Avg Count	3.6	boilers per site	6.7	boilers per site		
Estimate	25,382	boilers in UK (incl. domestic)	47,746	boilers in UK		
			34	domestic boilers in FOI data	11.5%	of boilers are domestic
			261	commercial boilers in FOI data		
			42,243	commercial boilers in UK Secondary Schools		
Universities						
Sites in UK	164	(Note: not premises, as per BEES data)				
Demand	23,817	kW/site (ECUK data)	6	sites in FOI	3.7%	of sites included in data
Avg Boiler	344	kW (from FOI data)	428	boilers in FOI		
Avg Count	69.2	boilers per site	71.3	boilers per site		
Estimate	11,342	boilers in UK (incl. domestic)	11,699	boilers in UK		
			42	domestic boilers in FOI data	13.5%	of boilers are domestic
			270	commercial boilers in FOI data		
			10,124	commercial boilers in UK Universities		



Fire and Ambulance

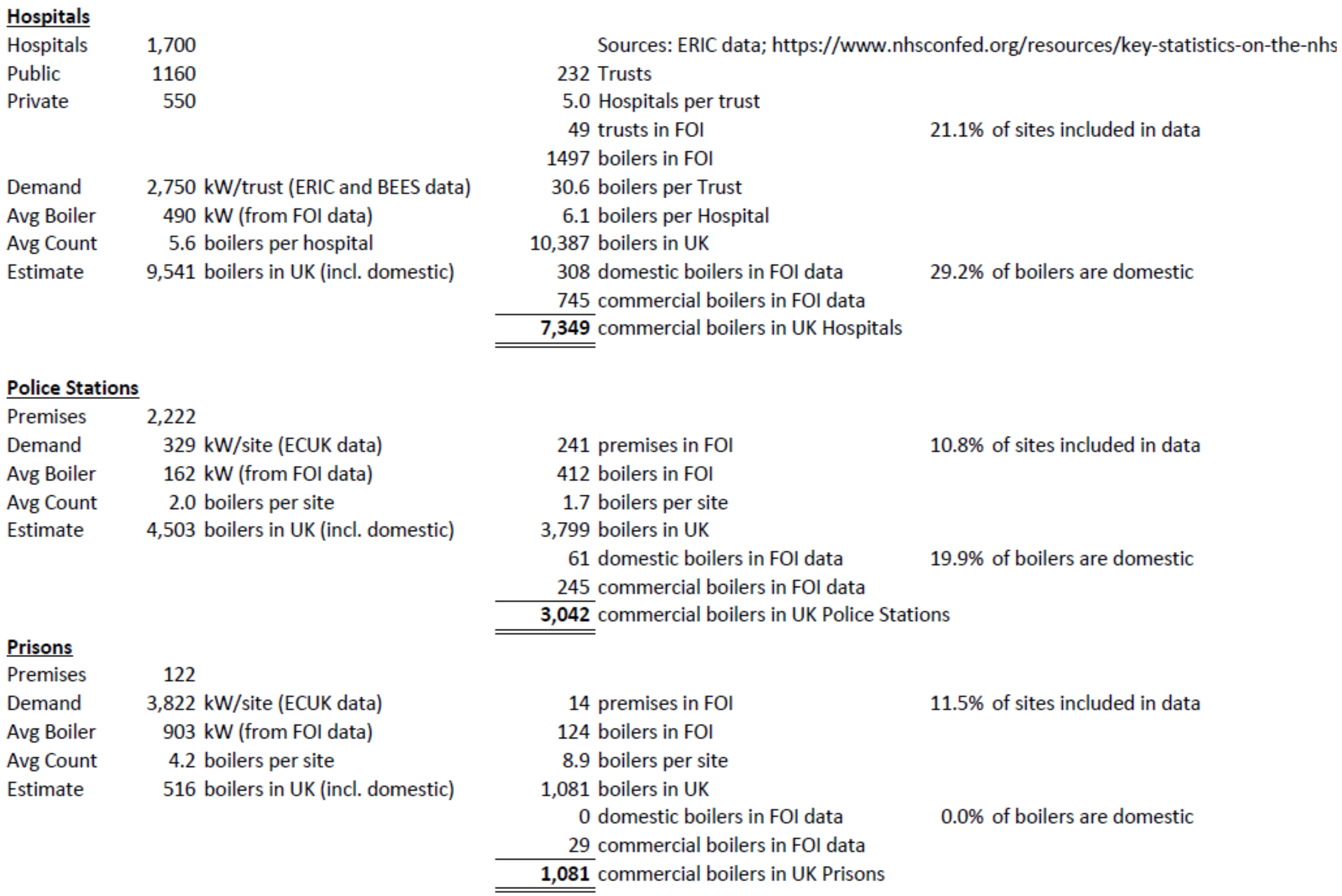
Sites in UK	4,000					
Demand	77	kW/site (ECUK data)	435	sites in FOI	10.9%	of sites included in data
Avg Boiler	47	kW (from FOI data)	700	boilers in FOI		
Avg Count	1.7	boilers per site	1.6	boilers per site		
Estimate	6,618	boilers in UK (incl. domestic)	6,437	boilers in UK		
			27	domestic boilers in FOI data	7.8%	of boilers are domestic
			320	commercial boilers in FOI data		
			5,936	commercial boilers in UK Fire and Ambulance		

Clubs and Community Centres

Premises	28,860			Source: BEES		
Demand	29	kW/site (ECUK data)	398	premises in FOI	1.4%	of sites included in data
Avg Boiler	97	kW (from FOI data)	668	boilers in FOI		
Avg Count	0.3	boilers per site	1.7	boilers per site		
Estimate	8,519	boilers in UK (incl. domestic)	48,438	boilers in UK		
			30	domestic boilers in FOI data	19.5%	of boilers are domestic
			124	commercial boilers in FOI data		
			39,002	commercial boilers in UK Clubs and Community Centres		

Leisure Centres

Premises	13,487			Source: BEES		
Demand	182	kW/site (ECUK data)	334	premises in FOI	2.5%	of sites included in data
Avg Boiler	273	kW (from FOI data)	371	boilers in FOI		
Avg Count	0.7	boilers per site	1.1	boilers per site		
Estimate	8,965	boilers in UK (incl. domestic)	14,981	boilers in UK		
			22	domestic boilers in FOI data	10.0%	of boilers are domestic
			197	commercial boilers in FOI data		
			13,476	commercial boilers in UK Leisure Centres		



Hospitals

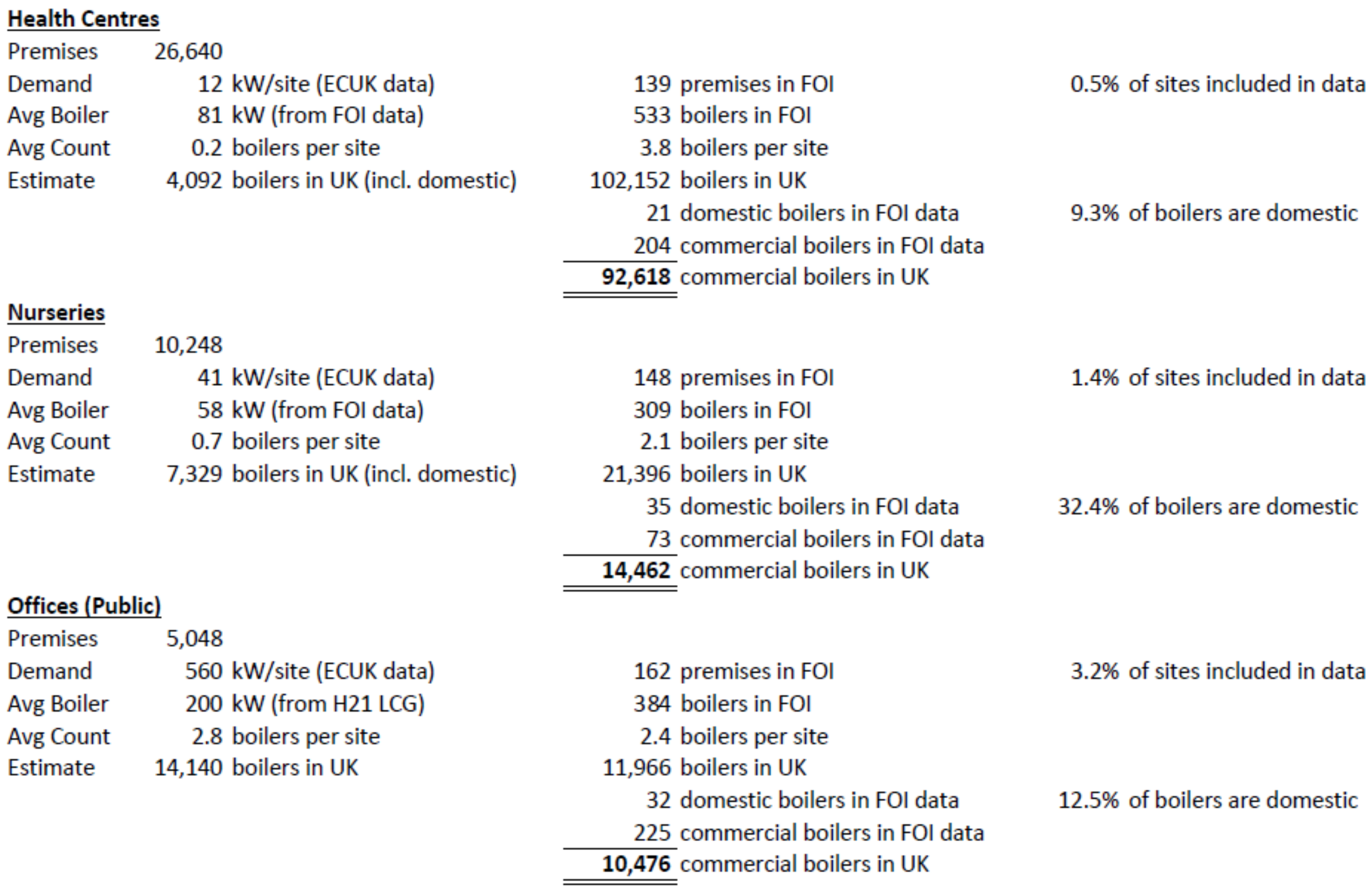
Hospitals	1,700			Sources: ERIC data; https://www.nhsconfed.org/resources/key-statistics-on-the-nhs		
Public	1160		232	Trusts		
Private	550		5.0	Hospitals per trust		
			49	trusts in FOI	21.1%	of sites included in data
			1497	boilers in FOI		
Demand	2,750	kW/trust (ERIC and BEES data)	30.6	boilers per Trust		
Avg Boiler	490	kW (from FOI data)	6.1	boilers per Hospital		
Avg Count	5.6	boilers per hospital	10,387	boilers in UK		
Estimate	9,541	boilers in UK (incl. domestic)	308	domestic boilers in FOI data	29.2%	of boilers are domestic
			745	commercial boilers in FOI data		
			7,349	commercial boilers in UK Hospitals		

Police Stations

Premises	2,222					
Demand	329	kW/site (ECUK data)	241	premises in FOI	10.8%	of sites included in data
Avg Boiler	162	kW (from FOI data)	412	boilers in FOI		
Avg Count	2.0	boilers per site	1.7	boilers per site		
Estimate	4,503	boilers in UK (incl. domestic)	3,799	boilers in UK		
			61	domestic boilers in FOI data	19.9%	of boilers are domestic
			245	commercial boilers in FOI data		
			3,042	commercial boilers in UK Police Stations		

Prisons

Premises	122					
Demand	3,822	kW/site (ECUK data)	14	premises in FOI	11.5%	of sites included in data
Avg Boiler	903	kW (from FOI data)	124	boilers in FOI		
Avg Count	4.2	boilers per site	8.9	boilers per site		
Estimate	516	boilers in UK (incl. domestic)	1,081	boilers in UK		
			0	domestic boilers in FOI data	0.0%	of boilers are domestic
			29	commercial boilers in FOI data		
			1,081	commercial boilers in UK Prisons		



Health Centres

Premises	26,640					
Demand	12	kW/site (ECUK data)	139	premises in FOI	0.5%	of sites included in data
Avg Boiler	81	kW (from FOI data)	533	boilers in FOI		
Avg Count	0.2	boilers per site	3.8	boilers per site		
Estimate	4,092	boilers in UK (incl. domestic)	102,152	boilers in UK		
			21	domestic boilers in FOI data	9.3%	of boilers are domestic
			204	commercial boilers in FOI data		
			92,618	commercial boilers in UK		

Nurseries

Premises	10,248					
Demand	41	kW/site (ECUK data)	148	premises in FOI	1.4%	of sites included in data
Avg Boiler	58	kW (from FOI data)	309	boilers in FOI		
Avg Count	0.7	boilers per site	2.1	boilers per site		
Estimate	7,329	boilers in UK (incl. domestic)	21,396	boilers in UK		
			35	domestic boilers in FOI data	32.4%	of boilers are domestic
			73	commercial boilers in FOI data		
			14,462	commercial boilers in UK		

Offices (Public)

Premises	5,048					
Demand	560	kW/site (ECUK data)	162	premises in FOI	3.2%	of sites included in data
Avg Boiler	200	kW (from H21 LCG)	384	boilers in FOI		
Avg Count	2.8	boilers per site	2.4	boilers per site		
Estimate	14,140	boilers in UK	11,966	boilers in UK		
			32	domestic boilers in FOI data	12.5%	of boilers are domestic
			225	commercial boilers in FOI data		
			10,476	commercial boilers in UK		

10.4 Appendix D: Technical Challenge Review

Table 10-1 – Component Level Technical Challenges - Review

Description	Title	Potential issue	Discussion (Level of challenge, difficulty to overcome, evidence, further work required, etc.)
Fuel Feed			
Diffusion of hydrogen atoms and/or molecules into the structure of a material, increasing pressure at the material grain boundaries. This pressure rise reduces the material ductility, toughness and tensile strength. Metals with high tensile strength (i.e. steel) are more vulnerable. Phenomenon is enhanced where high mechanical stress is present and can be further enhanced where temperature cycling is exhibited.	H_2 embrittlement	Failure of materials under a load, including piping, welds, etc.	The background mechanical and chemical theories that underpin H_2 embrittlement are fairly well understood. Prediction of material response within the UK delivery network and commercial appliances would require a material review of appliance build standards of all gas-seeing components. Overcoming this challenge would potentially require redesign of appliance components to remove any materials that were particularly susceptible to H_2 embrittlement and / or remove mechanical loading within components. Overall, it is proposed that this challenge can be viewed as onerous for designers and manufacturers as opposed to technically difficult.
The size of a hydrogen molecule is smaller than that of methane.	Fugitive leaks	Increased rate of fugitive leakage.	Hydrogen gas permeates markedly more quickly through both micro-separations (e.g. between flange connections) or polymeric structures (e.g. polyethylene) than methane. As a consequence, the rate of fugitive leakage would be predicted to increase markedly on the change from methane to hydrogen Careful selection of suitable polymeric materials in appliance design (e.g. flange seals) and design revision to reduce dry jointing (e.g. moving from flange joints to welded joints) may potentially aid reduction of fugitive

Description	Title	Potential issue	Discussion (Level of challenge, difficulty to overcome, evidence, further work required, etc.)
			leaks: however, further design-specific work would be required to confirm this. This challenge is one faced by all aspects of the gas network from hydrogen generation to client delivery and so would be best approached at a network-wide level. The present guidelines available for the confinement and movement of hydrogen suggest that the challenge is achievable but may require large-scale reassessment of the gas delivery network.
The process of displacement of air by hydrogen when commissioning/ re-starting hydrogen appliances creates flammable mixtures in unwanted sections of the appliance.	Purging	Unplanned internal ignition	The process of gas purging relies on the relative movement of gas molecules moving due to a pressure differential: this in turn relies on the relative density of gas molecules relative to each other. As differences in molecular mass increases (as is the case for natural gas, air and hydrogen) it requires longer purging periods to purge a heavier gas (e.g. natural gas) by a lighter gas (e.g. hydrogen). If purging is undertaken from gas feed to air (i.e. to purge new pipework), during the purge process the gas concentration within the pipework varies from 0% gas : 100% air to 100% gas : 0% air. During the purging period the gas: air concentration transitions from the Lower flammable limit (LFL) to Upper flammable limit (UFL) during which a flammable atmosphere is present. The LFL to UFL range for hydrogen : air mixtures differs markedly from that of NG : air with the hydrogen : air flammability curve being much wider (nominally 4-75% H_2 in air), In combination, the wider LFL – UFL range and the increased time to purge due to reduced molecular mass increases the time during which a flammable atmosphere is present.

Description	Title	Potential issue	Discussion (Level of challenge, difficulty to overcome, evidence, further work required, etc.)
			Due consideration and modification of purging techniques would be required for all appliances to ensure safe ignition and function, potentially achieving safe purge with the use of nitrogen as a carrier gas instead of air. This is achievable using present gas industry purging technologies but would add extra complexity into these procedures.
Aeration			
Flame speed of hydrogen (2.7 m/s) is greater than that of natural gas (0.37 m/s). Flame velocity could potentially exceed the velocity of gas fed to burner.	Light back (flash back)	Ignition of hydrogen/air mixture in confined parts of the appliance resulting in internal overpressure.	This challenge requires detailed assessment design-to-design of appliances in terms of the ignition and heating train. However, present small-scale hydrogen burner designs (e.g. braising torches) suggest that suitable aeration of larger burning surfaces should be achievable.
Ignition			
Hydrogen minimum ignition energy is much lower than natural gas.	Ignition energy	Unplanned or mistimed ignition	The minimum ignition energy (MIE) of hydrogen is significantly lower than that of natural gas resulting in increased risk of ignition during accidental release. However, within an appliance ignition system, the ignition energy from the ignitor is significantly higher than the MIE of either Hydrogen or natural gas. As a consequence, it is suggested that no modification of the ignitor mechanism would be expected to be required.
Volume of hydrogen / air build up within appliance prior to standard timing for natural gas ignition may result in explosion.	Ignition timing/ location	Explosion may cause damaging overpressure.	The timing of ignition (i.e. time from initial gas loading to the ignitor pulse) is potentially an area of concern due to the higher laminar flame speed of hydrogen. This may result in a higher over-pressure pulse at the start of reaction (i.e. prior to formation of a steady state burning

Description	Title	Potential issue	Discussion (Level of challenge, difficulty to overcome, evidence, further work required, etc.)
			surface at the burner) potentially affecting appliance integrity or function. An appliance review for each ignition cycle design would be required to ensure no damaging effects were introduced due to a change in gas type. It is proposed that this modification of the ignition train is achievable via design review.
High hydrogen flame speed relative to rate of gas supply may lead to flame instability.	Pilot flame	Mistimed ignition results in damaging overpressure.	Change of fuel gas into a given pilot flame design has a direct effect on flame profile. Generally with hydrogen flames burning on pilot flames designed for NG use, this is characterised by a reduction in flame length. This reduction in flame length then impinges on any flame monitoring apparatus fitted to a differing degree, so affecting how the appliances senses the flame. For any appliance incorporating a pilot flame scheduled for use with 100% hydrogen, a redesign of the pilot dimensions, gas flow rate and position of flame monitoring sensors would be required. It is proposed that this modification of the ignition train is achievable via design review.
Burner			
If gas supply velocity and flame speed are not well balanced, flame lift-off may occur.	Flame lift off	Unplanned flame impingement on appliance internals.	Based on the details given in earlier sections, this would require an appliance burner design review to ensure that burner design was suitable for safe and stable ignition of hydrogen flames.

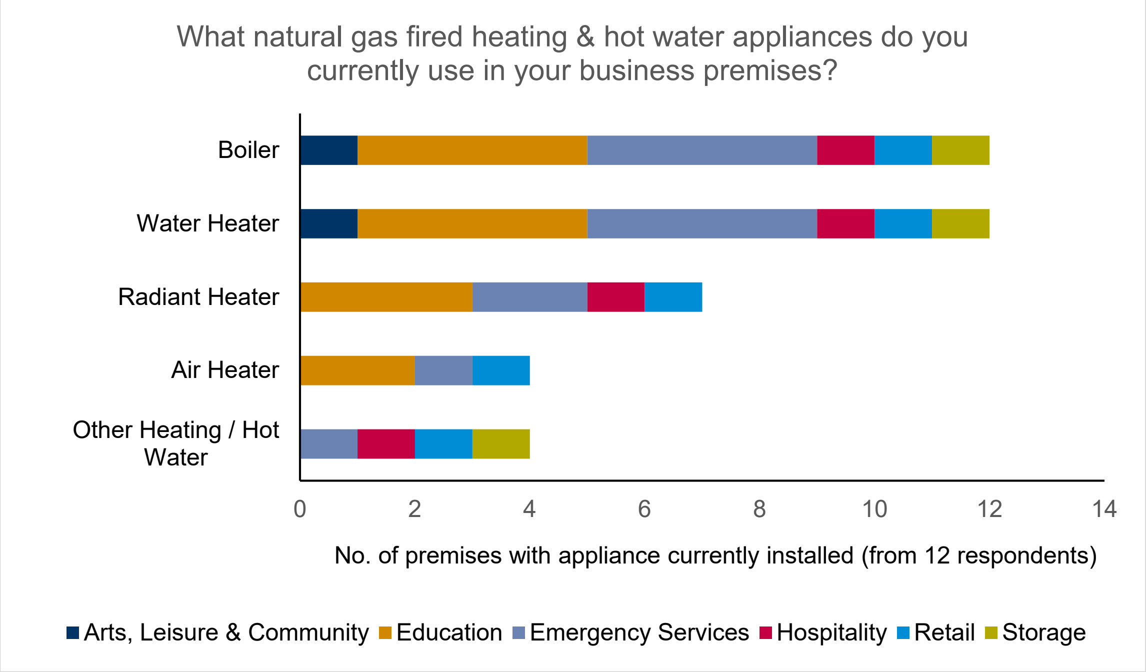
Description	Title	Potential issue	Discussion (Level of challenge, difficulty to overcome, evidence, further work required, etc.)
If gas supply velocity and flame speed are not well balanced, flame lift-off may occur.	Flame lift off	Inability to detect flame due to thermocouple position	Based on the details given in earlier sections, this would require an appliance burner design review to ensure that burner design was suitable for safe and stable ignition of hydrogen flames.
Flame speed of hydrogen (2.7 m/s) is greater than that of natural gas (0.37 m/s). Flame velocity could potentially exceed the velocity of gas fed to burner.	Light back (flash back)	Unplanned flame impingement on appliance internals	Based on the details given in earlier sections, this would require an appliance burner design review to ensure that burner design was suitable for safe and stable ignition of hydrogen flames.
Flame speed of hydrogen (2.7 m/s) is greater than that of natural gas (0.37 m/s). Flame velocity could potentially exceed the velocity of gas fed to burner.	Light back (flash back)	Loss of aesthetic quality of the appliance	Based on the details given in earlier sections, this would require an appliance burner design review to ensure that burner design was suitable for safe and stable ignition of hydrogen flames.
When burned, hydrogen does not produce as high a concentration of ions as natural gas.	Flame detection - ionisation	Ionisation sensors may not recognise the presence of hydrogen flame.	The reduction of ionic species in hydrogen combustion products will directly affect action threshold levels set within any ionisation-based detector. Ultraviolet (UV) based, hydrogen flame detectors in the automotive industry have been shown to provide a good alternative to detection in the visible range. Combined with the potential for shortening of the flame profile, this area of production design will require further review.
Luminosity of flame means it is less visible to the naked eye in daylight	Flame detection – visibility	It is not possible to visually identify easily if a flame has gone out or whether it is lit.	Flame luminosity is a product of the combustion chemistry of the fuel / air mixture. For pure hydrogen: air flames, the flame does not emit much light in the centre of the visible range but does emit light at the blue and red extremes. In conditions of intense light sources (e.g. sunlight), hydrogen emissions tend to be masked to the naked eye.

Description	Title	Potential issue	Discussion (Level of challenge, difficulty to overcome, evidence, further work required, etc.)
			This lack of luminosity is of significant concern during post-accident investigations where, for example, a gas line might have fractured and lit but first responders cannot see the flame. More markedly, the use of open flame appliances (e.g. hobs or chargrills) provide various routes by which burns to users may occur. For routine flame detection, flame detection could be determined by the use of alternative sensor technologies (e.g. thermal or UV detectors) linked to visible or audible alarms and these could be embodied within standard safe systems of work. Studies are on-going relating to the possible addition of low-level components into the hydrogen gas feed to colour the flame beyond the burner surface so as to aid visual detection. This challenge requires further scrutiny to safeguard both the public and routine users.
Luminosity of flame means it is not visible to the naked eye in daylight	Flame detection – visibility	Individuals may be physically harmed by contact with a colourless flame.	In addition to the details above on flame detection, addition of suitable guarding and access protocols (e.g. lockout) should be sufficient to ensure that operators do not come into contact with a live (but invisible) flame.
Heat Transfer (direct to target or to primary heating medium)			
Change in heat transfer kinetics due to different flame temperature/ profile, UV/IR emission characteristics and increased water vapour production.	Heat delivery	Reduced appliance efficiency	Based on the details given in earlier sections, this would require an appliance burner design review to ensure that burner design was suitable to achieve efficiency and heat transfer targets.

Description	Title	Potential issue	Discussion (Level of challenge, difficulty to overcome, evidence, further work required, etc.)
Change in heat transfer kinetics due to different flame temperature/ profile, UV/IR emission characteristics and increased water vapour production.	Heat delivery	Cannot achieve functional goal of the appliance	Based on the details given in earlier sections, this would require an appliance burner design review to ensure that burner design was suitable to achieve efficiency and heat transfer targets.
Increased hydrogen flame temperature may increase production of NO_x	Flame temperature	NO_x emissions rates may exceed current air quality standards for gas appliances.	Production of NO_x in relation to hydrogen flames is most marked due to the direct reaction of oxygen and nitrogen at high temperature (~ 1300 Deg.C) to produce nitric oxide (which then reacts further to produce various NO_x species). The higher temperature of a hydrogen flame (2100 Deg.C approx.) compared to NG (1950 Deg.C approx.) will be expected to drive production of NO_x to higher concentrations but further study will be required to quantify the effect.
Handling of Combustion Products			
Combustion of hydrogen produces 60-70% more water vapour than methane.	Change in composition and volume of combustion products	Overloading designed condensate handling (e.g. sump volumes, pumping rates, etc.)	The output of burning NG is a mixture of permanent gases (mainly CO / CO_2) and water produced as steam. By comparison, burning of hydrogen results in the formation of solely steam and no permanent gases. This change in production of permanent gases and the potential for water vapour to condense on colder parts of any appliance design (particularly within flues) means that flow characteristics of combustion products will differ significantly between NG and hydrogen combustion. A possible increase in corrosion due to the quantities of water present or in the post-burner location of heat

Description	Title	Potential issue	Discussion (Level of challenge, difficulty to overcome, evidence, further work required, etc.)
			deposited in appliance may occur due to the change in feed gas. However, it is proposed that careful review and modification of appliance burner and flue design should be able to ensure that burner / flue design is suitable for safe and stable processing of hydrogen combustion products. .
Combustion of hydrogen produces 60-70% more water vapour than methane.	Change in composition and volume of combustion products	Water vapour/ condensate in unplanned parts of appliance – “steam attack”/ corrosion	As above.
GENERAL			
Use of incompatible materials or flow of fluids within appliance may generate static potential energy.	Static	Auto-ignition of hydrogen/air mixture due to electrostatic discharge.	The electrostatic charging of materials is based in the theory of triboelectric charging. In this theory, the contact and eventual separation of dissimilar materials leads to charge transfer between the two materials (and this charge is then available to discharge to earth at a later time). Charge is generally accumulated to a higher level on polymeric or insulating materials compared to metal. Careful review and (as necessary) modification of appliance design should be able to ensure that triboelectric charging does not progress to a level to ignite hydrogen / air mixtures.
Changing flow rates of gaseous materials	Noise	Increased need for hearing protection or nuisance complaints	As flow rates of inlet gases or outlet combustion products changes, this may affect the turbulence of gas movement within pipework sections, potentially affecting noise production as the gas flows or exits the section.

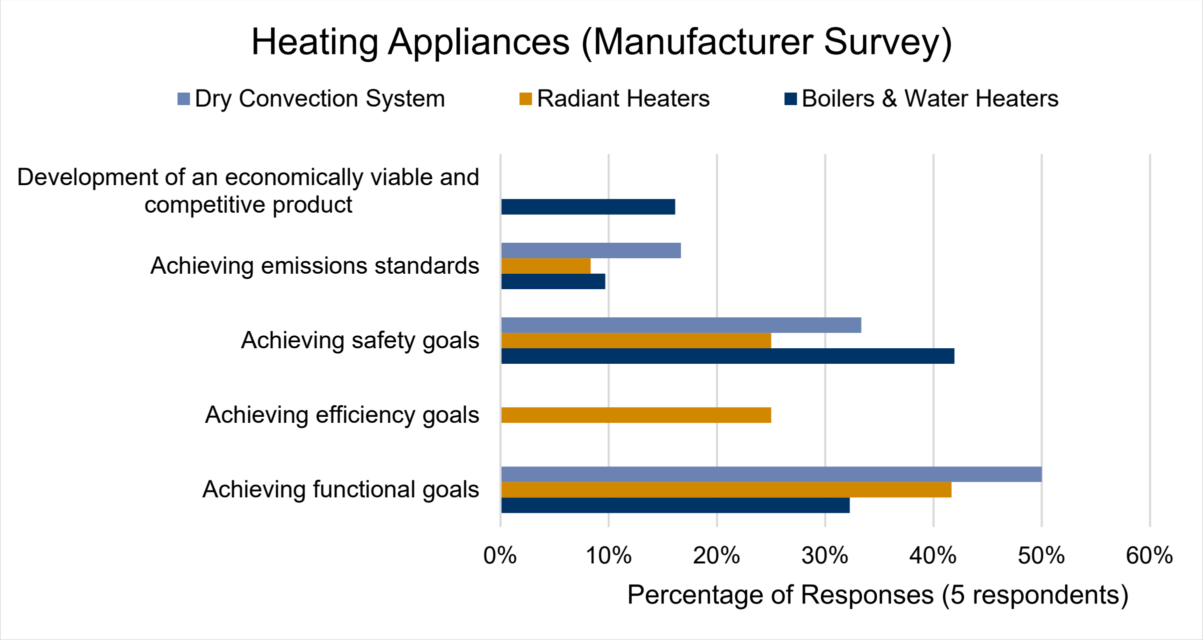
10.5 Appendix E: Survey Responses:

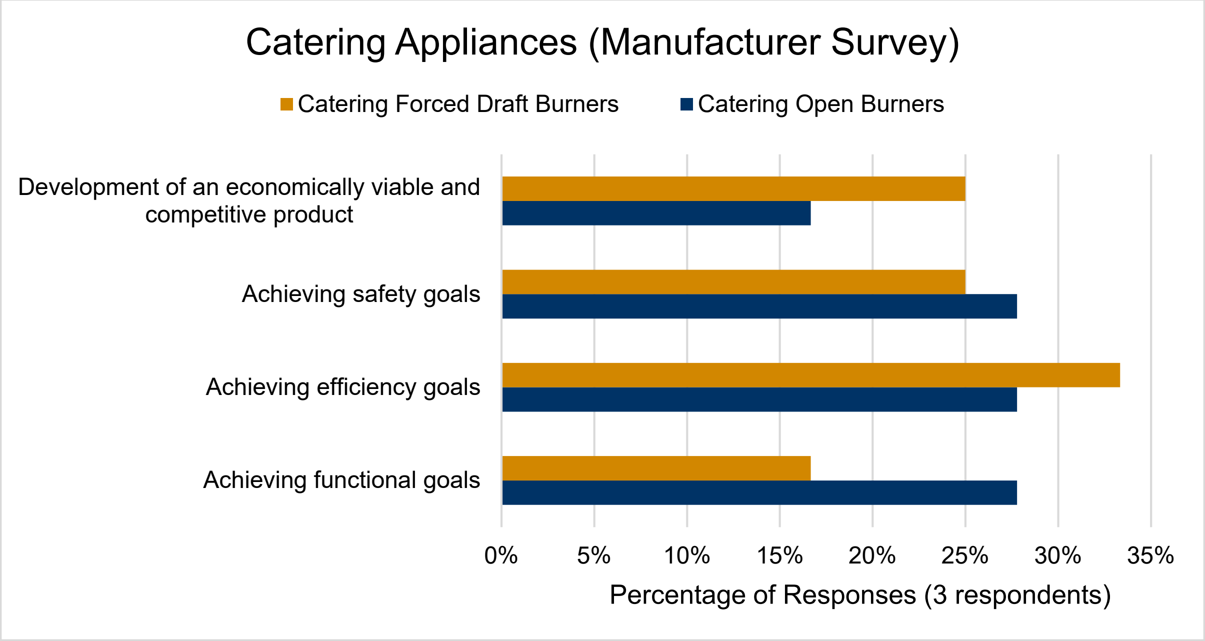


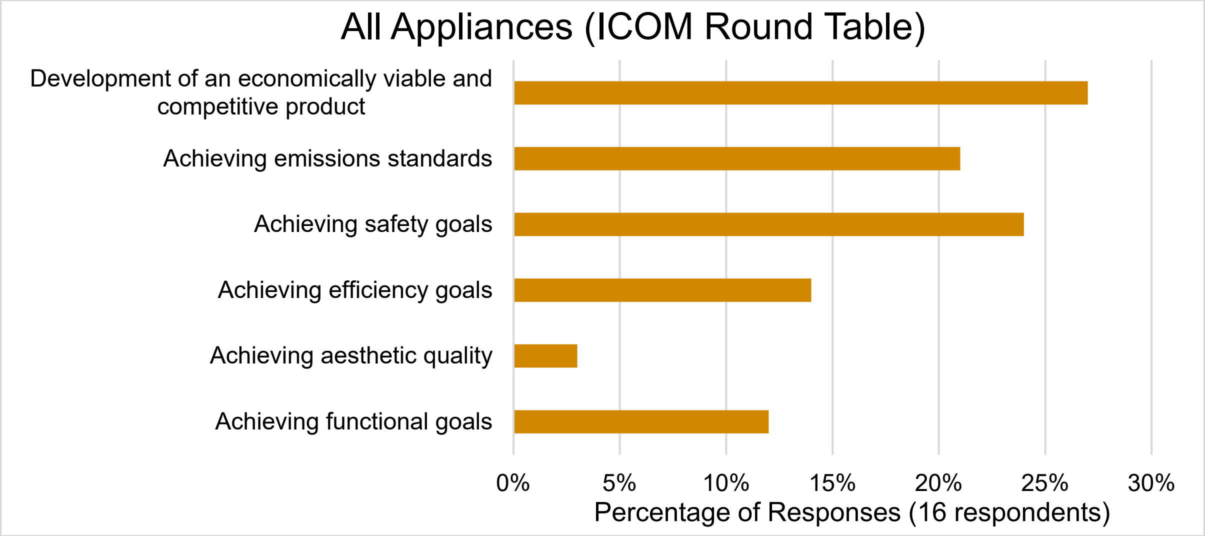
Heating and catering appliance manufacturers were asked within a survey to choose the three design goals they believed to be the hardest to achieve for a new appliance operating on 100% hydrogen. These were to be rated from 1 (hardest to achieve) to 3 ("easiest" to achieve) and the answers were weighted as such.

The choices given were; achieving functional goals, achieving aesthetic quality, achieving efficiency goals, achieving safety goals, achieving emissions standards, development of an economically viable and competitive product, or "other" (manufacturers given opportunity to provide alternative design goal).

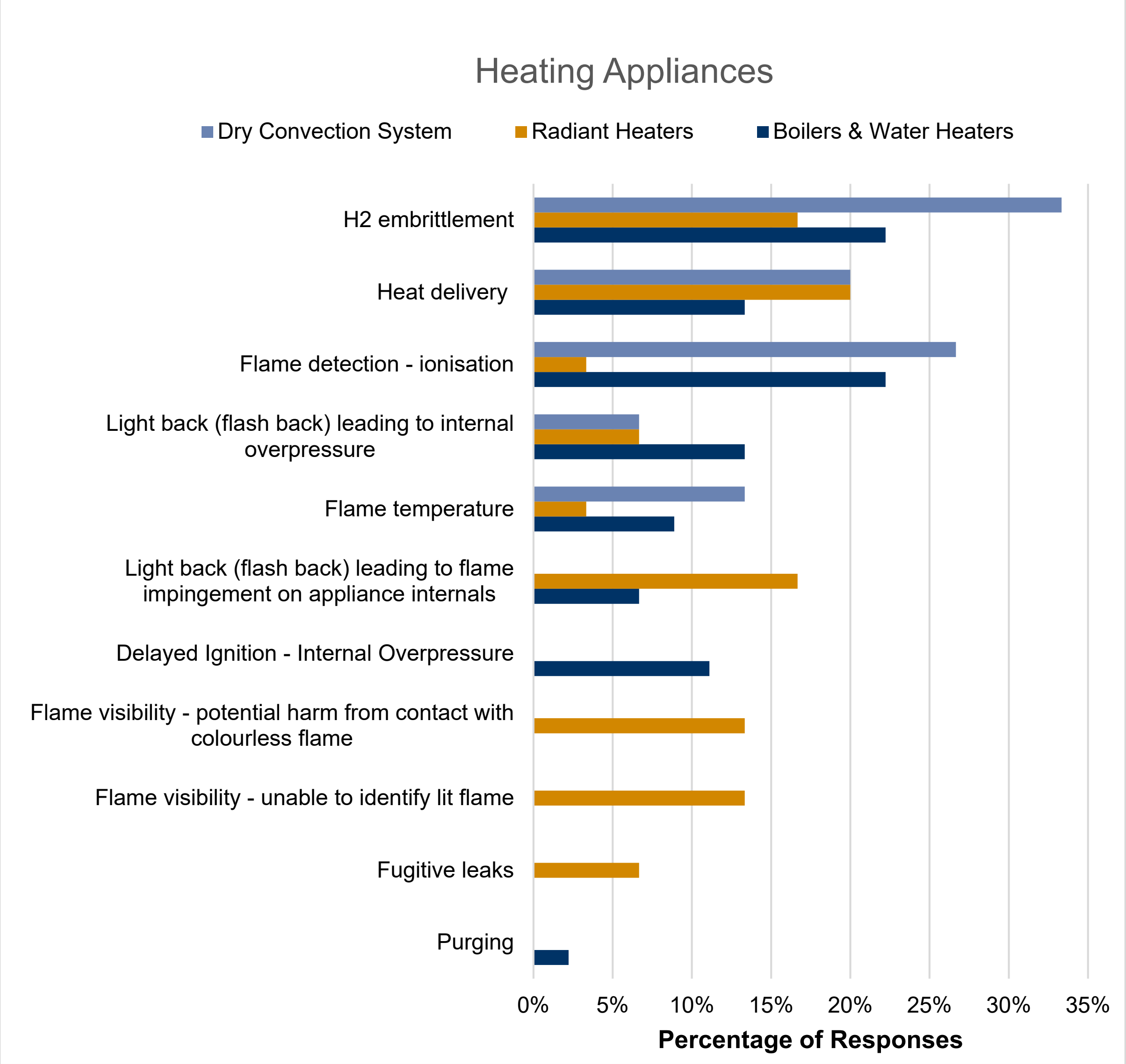
The same question was raised at a round-table discussion with the Industrial and Commercial Energy Association (ICOM) members, to noticeably different responses.

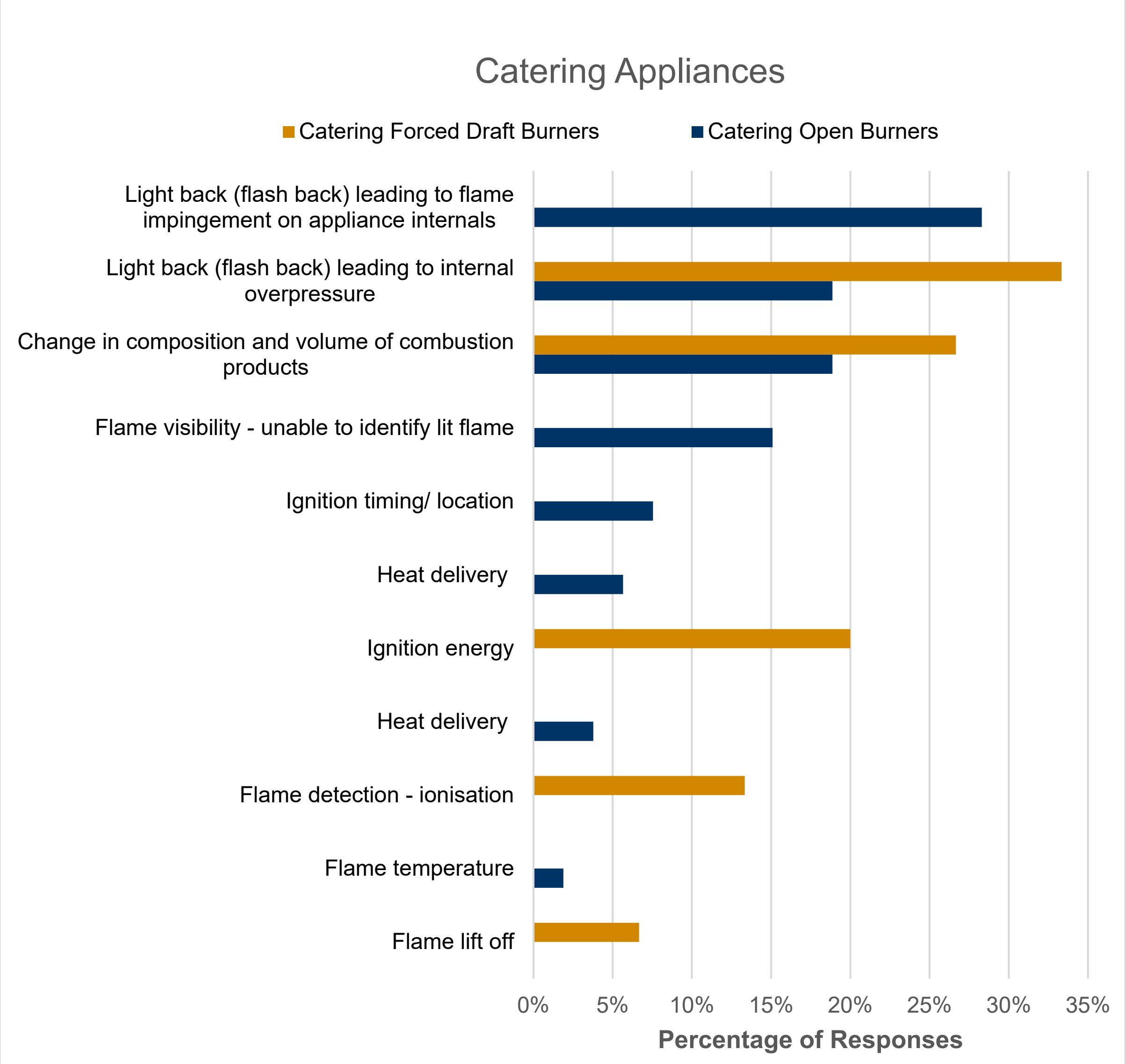


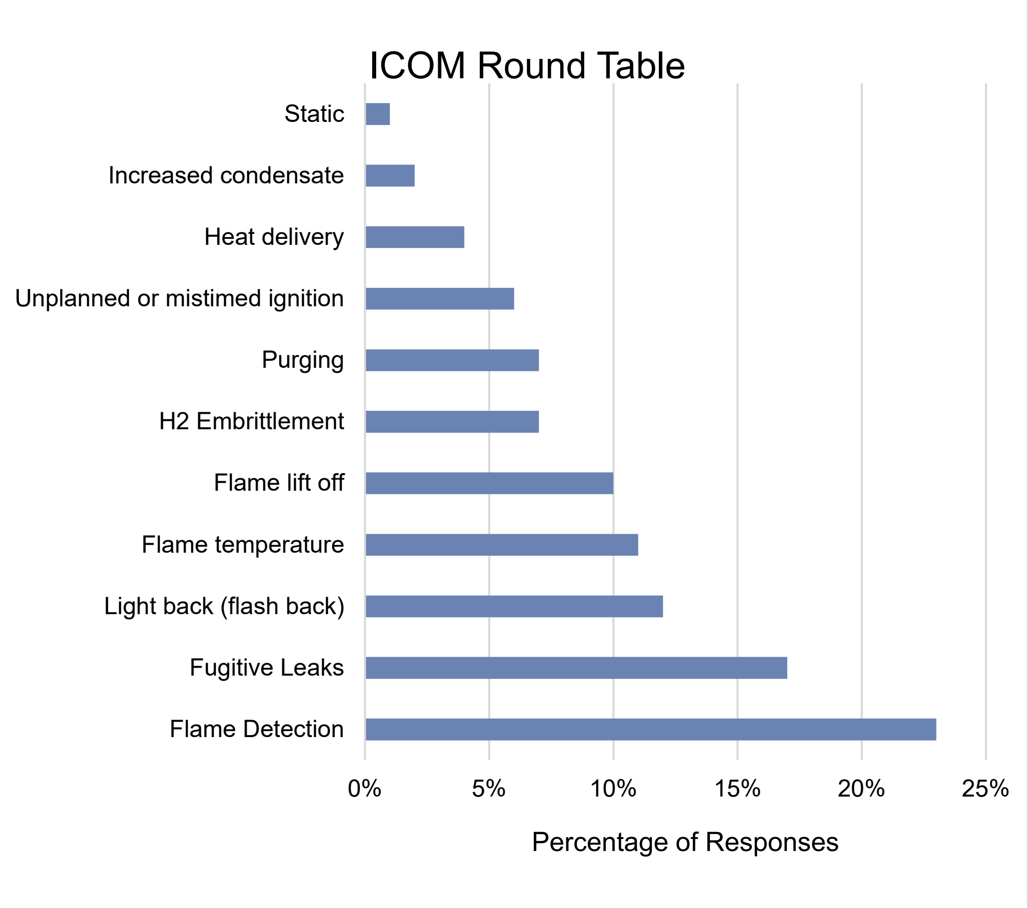




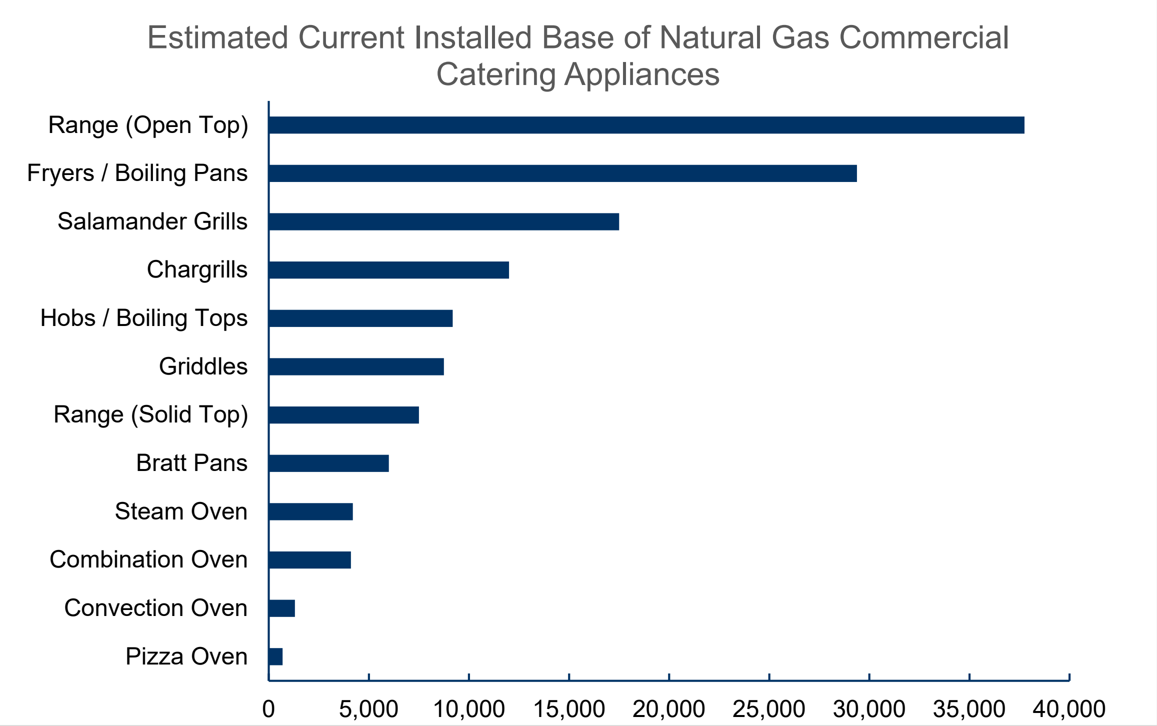
A further question was asked to rate component level challenges on a scale of 1 (greatest concern) to 5 (“least” concern).


Heating Appliances
Dry Convection System
Radiant Heaters
Boilers & Water Heaters
H2 embrittlement
Heat delivery
Flame detection - ionisation
Light back (flash back) leading to internal overpressure
Flame temperature
Light back (flash back) leading to flame impingement on appliance internals
Delayed Ignition - Internal Overpressure
Flame visibility - potential harm from contact with colourless flame
Flame visibility - unable to identify lit flame
Fugitive leaks
Purging
0%
5%
10%
15%
20%
25%
30%
35%
Percentage of Responses

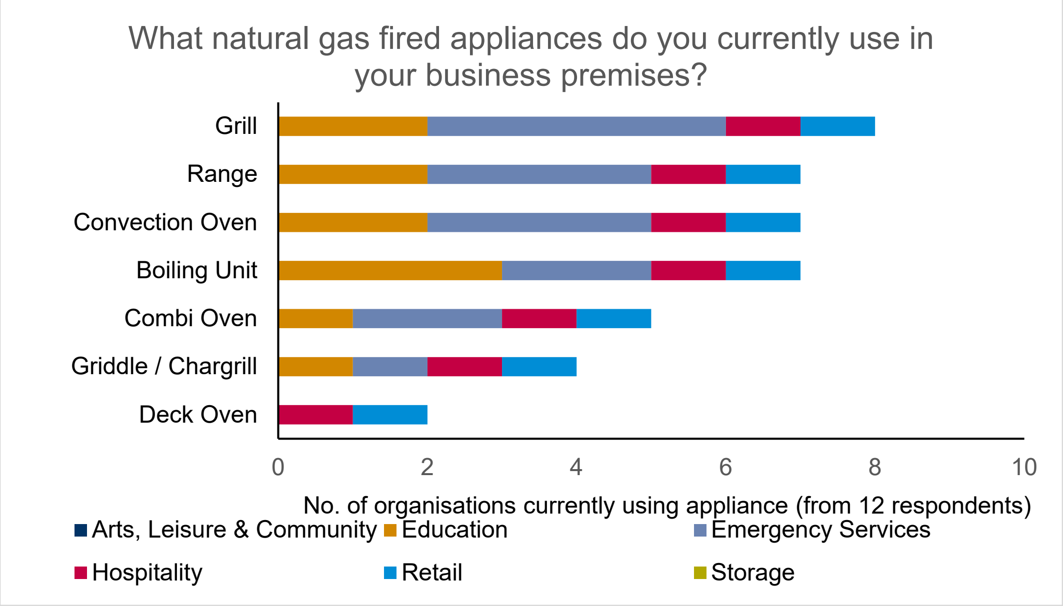

Catering Appliances
Catering Forced Draft Burners
Catering Open Burners
Light back (flash back) leading to flame impingement on appliance internals
Light back (flash back) leading to internal overpressure
Change in composition and volume of combustion products
Flame visibility - unable to identify lit flame
Ignition timing/ location
Heat delivery
Ignition energy
Heat delivery
Flame detection - ionisation
Flame temperature
Flame lift off
0%
5%
10%
15%
20%
25%
30%
35%
Percentage of Responses

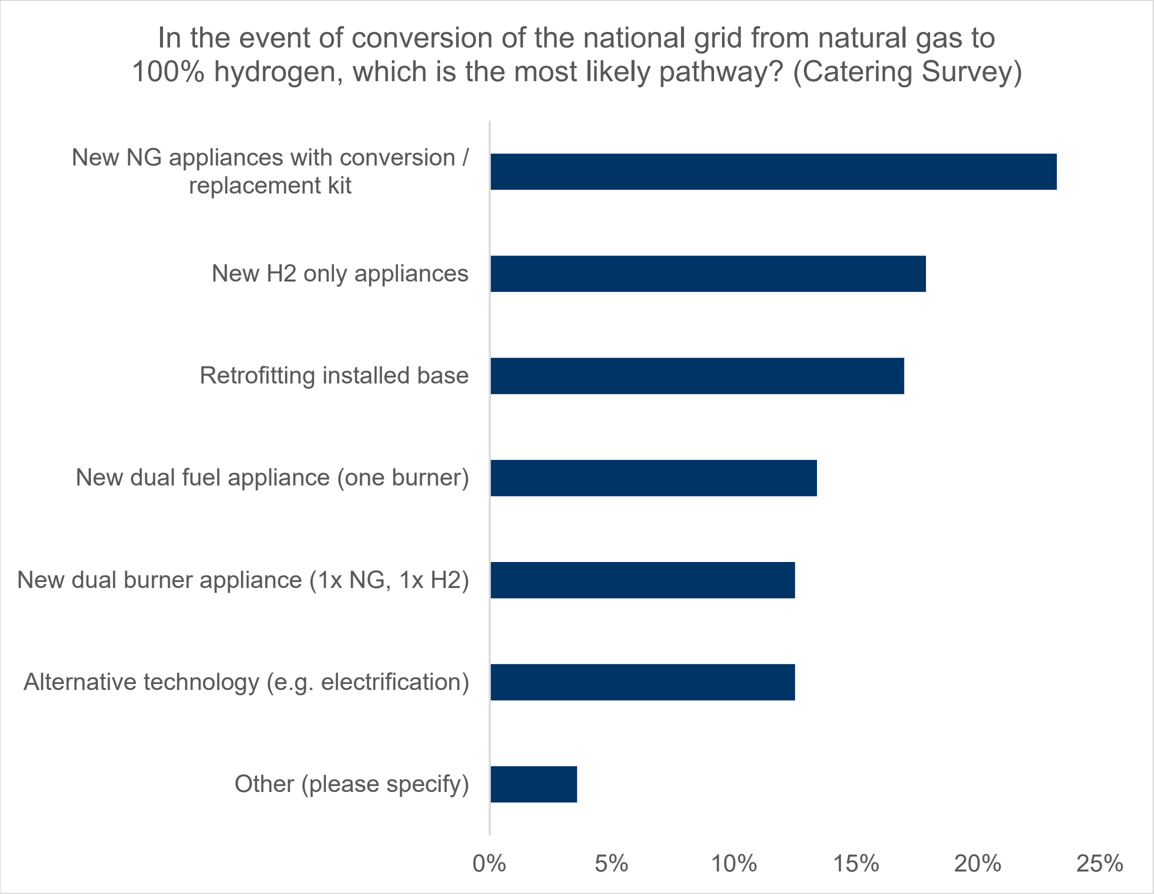


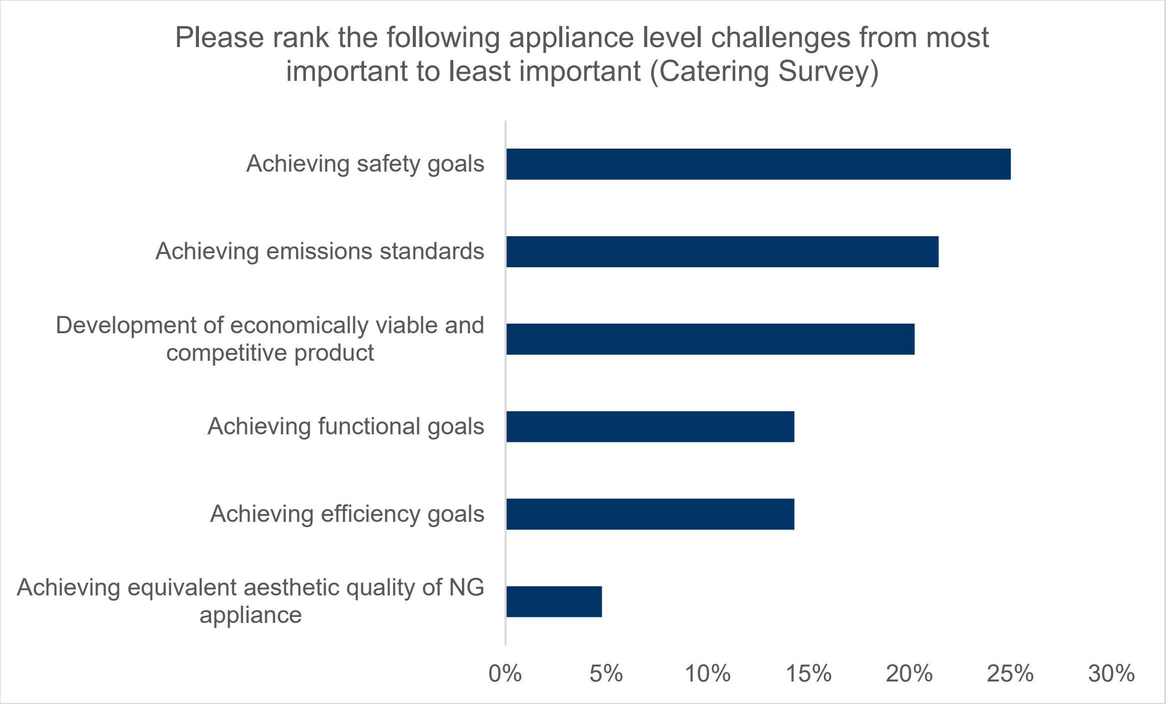
Estimates of the current installed base of natural gas commercial catering appliances were listed in a survey distributed to commercial catering appliance manufacturers. Respondents indicated how accurate they felt the numbers to be, from which new installed base estimates could be calculated.



As was the case with heating & hot water appliances, survey responses were gathered from various organisations which indicated which catering appliances were currently installed in their premises:






Please rank the following appliance level challenges from most important to least important (Catering Survey)
Achieving safety goals
Achieving emissions standards
Development of economically viable and competitive product
Achieving functional goals
Achieving efficiency goals
Achieving equivalent aesthetic quality of NG appliance
0%
5%
10%
15%
20%
25%
30%

10.7 Appendix F: Cost and Timeline Modelling

This Appendix includes the data tables for the cost and timeline modelling.

The table below presents the base case number of each type of appliance assumed for the purposes of the cost and timeline modelling.

Appliance #	Appliance type	Number of units in UK		
		Low capacity	Medium capacity	High capacity
1	Boilers (Pre-Mix)	212,000	276,897	3,776
2	Boilers (Package)	-	-	11,328
3	Air Heaters (Includes both direct and indirect)	160,000	200,000	40,000
4	Radiant Heaters (Includes both tube and plaque)	133,333	133,333	133,333
5	Water Heaters (includes both storage and instant)	18,000	182,000	-
6	Tumble dryers	22,000	22,000	22,000
7	Ovens (Combination)	1,333	1,334	1,333
8	Ovens (Bakery Deck / Rack)	3,333	3,334	3,333
9	Ovens (Pizza and convection)	1,000	1,000	1,000
10	Ovens (Steam)	2,000	2,000	2,000
11	Ranges	35,000	-	35,000
12	Hobs	6,000	-	6,000
13	Grills	15,000	-	15,000
14	Chargrills and griddles	17,500	-	17,500
15	Fryers	25,000	-	25,000
16	Boiling units and bratt pans	5,000	-	5,000
17	Others (kebab, rotisserie, tandoor)	10,000	-	10,000

The estimated cost for R&D and testing are outlined in the table below.

Appliance #	Appliance type	Estimated cost during R&D phase (£)	Estimated cost during testing phase (£)	Total cost for both R&D and testing (£)
1	Boilers (Pre-Mix)	145,836	446,994	592,830
2	Boilers (Package)	145,836	446,994	592,830
3	Air Heaters (Includes both direct and indirect)	113,171	346,873	460,044
4	Radiant Heaters (Includes both tube and plaque)	72,545	222,355	294,900
5	Water Heaters (includes both storage and instant)	106,642	326,861	433,503

Appliance #	Appliance type	Estimated cost during R&D phase (£)	Estimated cost during testing phase (£)	Total cost for both R&D and testing (£)
6	Tumble dryers	152,345	466,945	619,290
7	Ovens (Combination)	92,988	285,012	378,000
8	Ovens (Bakery Deck / Rack)	80,767	247,553	328,320
9	Ovens (Pizza and convection)	52,073	159,607	211,680
10	Ovens (Steam)	52,073	159,607	211,680
11	Ranges	55,261	169,379	224,640
12	Hobs	42,509	130,291	172,800
13	Grills	52,073	159,607	211,680
14	Chargrills and griddles	42,509	130,291	172,800
15	Fryers	52,073	159,607	211,680
16	Boiling units and bratt pans	42,509	130,291	172,800
17	Others (Kebab, Rotisserie, Tandoor)	52,073	159,607	211,680

The base case cost to convert or replace all units in the UK is presented below for each appliance type.

Appliance #	Appliance type	Average Capex per unit to convert (£)			Average Capex per unit to replace (£)			% replaced rather than converted (%)	UK Capex to convert or replace appliances (£)
		Low capacity	Medium capacity	High capacity	Low capacity	Medium capacity	High capacity		
1	Boilers (Pre-Mix)	3,331	4,850	8,150	12,892	16,250	58,100	50%	3,382,771,387
2	Boilers (Package)	3,413	5,125	8,975	15,152	19,350	71,663	50%	275,912,078
3	Air Heaters (Includes both direct and indirect)	3,275	4,750	6,813	10,683	15,333	22,825	50%	2,116,093,750
4	Radiant Heaters (Includes both tube and plaque)	2,940	3,592	4,454	5,269	7,087	10,725	50%	1,190,493,333

Appliance #	Appliance type	Average Capex per unit to convert (£)			Average Capex per unit to replace (£)			% replaced rather than converted (%)	UK Capex to convert or replace appliances (£)
		Low capacity	Medium capacity	High capacity	Low capacity	Medium capacity	High capacity		
5	Water Heaters (includes both storage and instant)	3,842	7,308	13,858	13,796	18,854	3,850	50%	2,166,714,484
6	Tumble dryers	3,310	5,029	10,983	11,807	20,048	99,330	50%	1,099,747,940
7	Ovens (Combination)	3,251	4,887	7,831	18,254	33,258	63,266	50%	57,049,647
8	Ovens (Bakery Deck/ Rack)	3,530	6,060	10,900	43,033	82,817	162,383	50%	312,315,038
9	Ovens (Pizza and convection)	2,810	3,280	4,050	5,833	13,583	21,333	50%	19,477,639
10	Ovens (Steam)	2,885	3,393	3,975	9,708	11,646	13,583	50%	36,125,069
11	Ranges	2,826	3,409	4,454	6,660	18,595	30,530	50%	554,344,583
12	Hobs	2,795	3,156	3,658	5,069	8,706	12,343	50%	58,927,433
13	Grills	2,826	3,255	3,838	6,660	10,638	14,617	50%	166,364,083
14	Chargrills and griddles	2,782	3,145	3,706	4,387	9,502	14,617	50%	180,631,403
15	Fryers	2,800	3,230	3,920	5,317	12,033	18,750	50%	296,738,889
16	Boiling units and bratt pans	2,780	3,105	3,560	4,283	7,642	11,000	50%	46,039,306
17	Others (kebab, rotisserie, tandoor)	2,820	3,245	3,840	6,350	10,742	15,133	50%	111,401,944

The assumptions used in the Monte Carlo analysis are presented in the following table.

Input	Unit	Type of distribution	Base-case level	Parameter 1: Mean	Parameter 2: Standard deviation
For each level of complexity, labour time needed increases by	Hours	Normal	1.1	1.1	0.11
For each level of complexity, equipment cost increases by	%	Normal	0.05	0.05	0.005

Input	Unit	Type of distribution	Base-case level	Parameter 1: Mean	Parameter 2: Standard deviation
Survey cost	£	Normal	300	300	30
Ancillary works cost	£	Normal	2500	2500	250
Hours required for installation (pre-mix boiler, from which other appliances are derived)	Hours	Normal	12	12	1.2
Factor increase for hydrogen appliance price compared to natural gas appliance	Number	Pert	2.5	2.5	N/A for Pert distribution. Min: 1.5 Max: 4

In order to determine the number of each type of appliance in the UK in the Monte Carlo analysis, a Pert distribution was applied based on the parameters below:

Appliance #	Appliance type	Mean total number of appliances	Min number of appliances	Max number of appliances
1	Boilers (Pre-Mix)	492,672	403,229	547,414
2	Boilers (Package)	11,328	9,271	12,586
3	Air Heaters (Includes both direct and indirect)	300,000	180,000	360,000
4	Radiant Heaters (Includes both tube and plaque)	240,000	120,000	360,000
5	Water Heaters (includes both storage and instant)	200,000	165,000	220,000
6	Tumble dryers	66,000	50,000	80,000
7	Ovens (Combination)	4,000	2,000	6,000
8	Ovens (Bakery Deck / Rack)	10,000	6,000	16,000
9	Ovens (Pizza and convection)	3,000	2,000	5,000
10	Ovens (Steam)	6,000	4,000	10,000
11	Ranges	70,000	42,000	112,000
12	Hobs	12,000	7,000	19,000
13	Grills	30,000	18,000	48,000
14	Chargrills and griddles	35,000	21,000	56,000
15	Fryers	50,000	30,000	80,000

Appliance #	Appliance type	Mean total number of appliances	Min number of appliances	Max number of appliances
16	Boiling units and bratt pans	10,000	6,000	16,000
17	Others (kebab, rotisserie, tandoor)	20,000	12,000	32,000

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