Department for
Energy Security
& Net Zero

Evaluation of Hy4Heat

Final report

February 2023

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Executive Summary

About the programme

Launched in 2017, Hy4Heat's mission was to establish if it is technically possible, safe and convenient to replace natural gas (methane) with hydrogen in residential and commercial buildings and gas appliances. This aimed to enable the government to determine whether to proceed to a community trial to test the implementation of hydrogen in residential buildings.

A core aim of Hy4Heat was to develop a range of new, First-of-a-Kind (FOAK) domestic heating and cooking appliance prototypes. More specifically, the programme had two primary objectives:

- To provide the technical, performance, usability and safety evidence needed to de-risk the viability assessment of hydrogen heating in buildings
- To stimulate industry to undertake a parallel programme of technical, performance and safety work on the distribution network.

The programme consisted of ten distinct but inter-linked work packages (WPs), covering areas such as domestic appliances, commercial appliances, meters, appliance certification, and a safety assessment. A further work package, led by Arup+, focused on programme and technical management.

The adaptable nature of the programme design meant that it could introduce new work packages or work strands to help address newly identified and/or ongoing technical concerns as they emerged.

Aims and purpose of the evaluation

DESNZ commissioned a process, impact and economic evaluation of Hy4Heat, aiming to address the following high-level questions:

1. What impact has the programme had?
2. How has the programme achieved these impacts?
3. How effective and efficient has the programme delivery plan been?
4. What is the overall cost-effectiveness of the programme?
5. What is the wider learning from the evaluation for DESNZ?

Methods used

The evaluation took a mixed-method, theory-based approach. Specifically, it has used a Contribution Analysis with Process Tracing, to assess the contribution of the programme towards meetings its intended outcomes and impacts. An economic Value for Money assessment took place alongside this.

The study has drawn on evidence from the following:

- Investment trend analysis – examining changes in variables such as equity investment, changes in firm valuation, and awarding of public funding for hydrogen R&D
- Patent data analysis
- Review of comparator international programmes
- Review of programme data and documentation – including the programme business cases, Key Performance Indicator (KPI) data, and invitations to tender for each work package
- Bespoke interview programme – this involved 79 interviews covering work package lead contractors, external national and international stakeholders, and government representatives.

Outcomes and Impacts of Hy4Heat

Hy4Heat has successfully developed a range of functioning appliance prototypes to demonstration phase. The work package contractors focusing on appliance development have, on average, seen a mean TRL[1] increase of 3.2, marginally higher than the average seen in other DESNZ energy innovation programmes.

- Most contractors reported an **expectation that their technologies would have reached at least TRL 6** (a functioning protype) by the end of Hy4Heat. In line with this, for many, further work is still needed to test product reliability before implementation in a demonstrator or real-life setting. Further work is also needed to scale-up manufacturing processes before commercialisation of appliances can occur.
- Several work package (WP) contractors and wider stakeholders felt that one of Hy4Heat's most important achievements was the receipt of **a letter of assistance from the Health and Safety Executive (HSE)**, confirming the relevance of the safety assessment developed as part of Hy4Heat. This shows that there are no substantial safety barriers to the introduction of hydrogen for heating system demonstrators.
- Evidence from interviews and reviews of programme documentation strongly suggests that **Hy4Heat has informed policy on the continuation of hydrogen for heating R&D to community trial stage**. For instance, Hy4Heat outputs helped inform the decision to continue with the H100 project which will convert 300 homes to hydrogen. The results of Hy4Heat also contributed towards Government commitments to work with industry to develop larger scale hydrogen heating trials by the middle of the decade, as outlined in the Government's *Ten Point Plan for a Green Industrial Revolution.*[2]
- Hy4Heat evidence has **informed parallel R&D investment programmes, particularly with Gas Distribution Network Operators (GDNOs)** who have drawn on Hy4Heat's

[1] Technology Readiness Level (TRL). This is a measurement system used to categorise the maturity level of a particular technology. There are nine TRLS, with TRL1 being the lowest and TRL9 being the highest. For further details, see https://www.nasa.gov/directorates/heo/scan/engineering/technology/technology_readiness_level (accessed 21 October 2021)

[2] Available at https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/936567/10_POINT_PLAN_BOOKLET.pdf

safety assessment, giving them greater confidence to continue with their work on the upstream elements of hydrogen for heating solutions. Hy4Heat has also influenced international R&D activity with international stakeholders. For example, with gas network providers in other countries and non-UK sister companies of Hy4Heat contractors approaching Hy4Heat contractors to gather information to inform their own work.

- The First-of-a-Kind heating and cooking appliances developed through Hy4Heat have raised the potential for UK contractor firms to gain a first mover advantage through future export opportunities. However, there is little evidence to date that the UK has derived many tangible economic benefits from this first mover advantage. Relatively few other countries are actively progressing hydrogen for domestic heating, meaning there are currently few opportunities for UK contractors to exploit.

Value for Money

The majority of stakeholders felt that the programme management was of a high quality and delivered at an appropriate cost, particularly given the scale of the programme and the wide variety of work packages that required monitoring and risk management.

The cost to the public purse per TRL achieved across appliance development work packages was £0.2 million. On average, the cost per TRL advancement was lowest in WP5 (commercial appliances) at just under £0.2 million and highest in WP10 (hydrogen meters) at £0.3 million, with limited variation between the work packages. This compares favourably to the cost of commensurate TRL uplifts across the wider Energy Innovation Portfolio (EIP, excluding Hy4Heat) – at £0.6 million. However, it should be noted that EIP programmes support innovation across a wide range of technologies, which face inherently different challenges and costs in their development, so the programmes are not directly comparable.

- **Hy4Heat has stimulated wider industry to invest in hydrogen research.** Some of the appliance manufacturers not involved in the programme have since become involved in industry wide discussions around the use of hydrogen in the gas network. Additionally, some external appliance manufacturers have now made public commitments to develop their own hydrogen ready products. This indicates that the programme has been successful in leveraging further R&D expenditure and activity, although it is not possible to estimate a leverage ratio.

Effectiveness of programme design and delivery processes

Overall, the application, assessment and procurement processes appear to have worked well. The different tendering processes used were straightforward to understand, the scope of work was clear, and assessment panels (where used) were appropriately staffed. However, the assessment process at times took longer than expected. Bidders valued the early interaction DESNZ had with them when devising the scope of works. Part of Arup+'s remit was to facilitate knowledge exchange and interactions between the different work packages.

- **Some respondents felt that having a programme management contractor in place (Arup+) facilitated more efficient programme management.** Given the breadth of coverage of Hy4Heat's ten WPs, it was effective to have a programme management contractor to monitor progress, identify and assess risks and to coordinate requests to

DESNZ for information. Arup+ also acted as a reliable resource for securing input from experts to advise on technical matters throughout the programme, particularly in relation to the safety assessment.

- **For other WP contractors more accustomed to direct engagement with DESNZ, some felt the programme management contractor role created an extra layer of bureaucracy, and prevented direct access to DESNZ officials.** However, the DESNZ team managing Hy4Heat would not have had sufficient resource to directly manage and engage with all WP contractors on a more frequent basis.
- The programme's **wider stakeholder engagement and dissemination has been effective**, with the programme gaining international traction, and with a March 2020 stakeholder engagement event being attended by over 200 people.
- Many of Hy4Heat's core work packages were delivered through the Covid-19 pandemic. While this caused delays to project completion dates, the fact that Hy4Heat has, within this context, still been able to demonstrate that it is technically possible and safe to replace natural gas with hydrogen across a wide range of appliances and meters is a considerable success. Further work will be needed to understand the cost and feasibility of proposed safety measures, as well as to determine whether determine whether hydrogen can safely be used in distribution networks and wider types of building that were outside the scope of Hy4Heat.

Wider learning for DESNZ

- The Hy4Heat programme has a bespoke website which provides information on what the programme's aim and objectives are, what work is taking place in the individual Work Packages, progress made and project completion reports. The website provides more information, in one centralised source, than is commonly available for other DESNZ Energy Innovation Portfolio (EIP) programmes. Some industry stakeholders commented on the usefulness of the Hy4Heat website as a centralised source of information, alongside e-newsletters and stakeholder engagement events. Developing individual programme websites may not be appropriate or necessary for all EIP or NZIP programmes, but may be considered useful for programmes which have a similar emphasis on working collaboratively with industry to meet longer term goals on advancing technology development and deployment.
- Some respondents interviewed felt that the original aims of Hy4Heat were broad ranging and created some uncertainty on the scope of work. Hy4Heat has developed a limited range of commercial appliance prototypes and the scope of safety work in buildings was limited to certain types of residential buildings, rather than all types of residential and commercial buildings. The rationale for this prioritisation was that it maximises use of available time and budget to provide sufficient evidence to enable development of the first neighbourhood trial to proceed (focusing on types of residential properties within this scope). When prioritisation in the focus of programme aims occurred, the implications for remaining evidence gaps could have been more clearly documented and communicated to wider policy teams. A learning point is that clear communication of what evidence a programme will and will not provide, would provide timely information to inform decisions on what future R&D needs to be commissioned and when strategic decisions on decarbonisation pathways can be made.

Introduction

The Department for Energy Security and Net Zero (DESNZ) appointed Technopolis Ltd in collaboration with Ipsos MORI and George Barrett to conduct a process, impact and economic evaluation of the Hy4Heat programme. This Introduction Section provides an overview of the aims of the Hy4Heat programme, the purpose of the evaluation and an overview of the methods used.

Hy4Heat Programme aims and design

Hy4Heat's mission was to establish if it is technically possible, safe and convenient to replace natural gas (methane) with hydrogen in residential and commercial buildings and gas appliances. This aimed to enable the government to determine whether to proceed to a community trial to test the implementation of hydrogen in residential buildings[3]. At the time of programme launch in late 2017, evidence was needed on hydrogen's suitability for heating in terms of:

- Safety
- Cost and affordability
- Practical performance – integrity (e.g., impact on materials), and efficiency
- Durability/longevity of appliances
- System capacity
- Consumer usability and impact acceptance in residential buildings, and in gas appliances.

A core aim of Hy4Heat was to develop a range of new, First-of-a-kind (FOAK) domestic heating and cooking appliance prototypes. More specifically, the programme had two primary objectives:

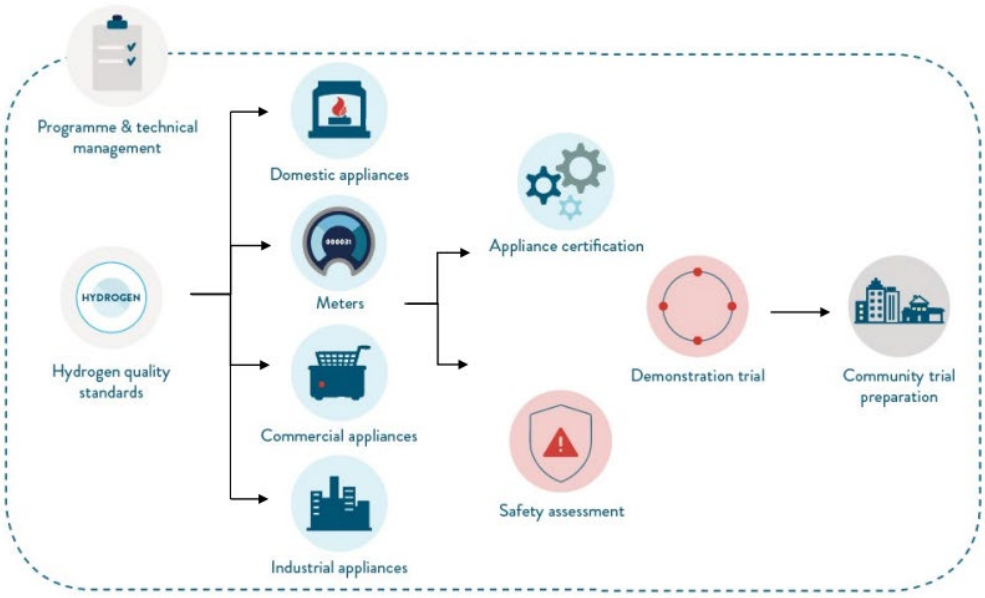
- To provide the technical, performance, usability and safety evidence needed to de-risk the viability assessment of hydrogen heating in buildings
- To stimulate industry to undertake a parallel programme of technical, performance and safety work on the distribution network.

More broadly, the outcomes of the Hy4Heat programme will help DESNZ understand if hydrogen-based heating is a viable pathway for decarbonising heat and contribute to achieving net zero carbon emissions targets by 2050. Hy4Heat was funded (with ~£25m) as one programme within the wider ~£505m DESNZ Energy Innovation Portfolio. Hy4Heat sits alongside other innovation programmes designed to develop different parts of the hydrogen supply and conversion chain (including the Hydrogen Supply and Industrial Fuel Switching programmes).

[3] Adapted from Hy4Heat website, https://www.hy4heat.info (accessed 20 October 2021)

The programme consisted of ten distinct but inter-linked work packages (as per Figure 1 below), each of which operated to different procurement and delivery timescales. The adaptable nature of the programme design meant that it could introduce new work packages or work strands to help address newly identified and/or ongoing technical concerns as they emerged.

Figure 1: Summary Overview of Hy4Heat work packages



Source: Hy4Heat website

Aims and purpose of the evaluation

DESNZ commissioned a process, impact and economic evaluation of the Hy4Heat programme, with specific focus on:

- Identifying the overall programme benefits and impacts
- Assessing the extent to which the programme has achieved its objectives, success criteria and KPIs for the programme; including whether the evidence needs of the policy teams have been met to inform decisions on progressing with a community trial
- Assessing the cost effectiveness of the programme by understanding the issues associated with value for money and comparing Hy4Heat's cost effectiveness to other similar innovation programmes
- Understanding the effectiveness and efficiency of programme implementation, including an assessment of the effectiveness and efficiency of the contracted project management, procurement structures, and internal governance structures. This will provide learning to inform design of future Net Zero Innovation Portfolio programmes as well as parallel programmes of R&D within the hydrogen innovation landscape.

The evaluation aims to address the following high-level questions:

6. What impact has the programme had?

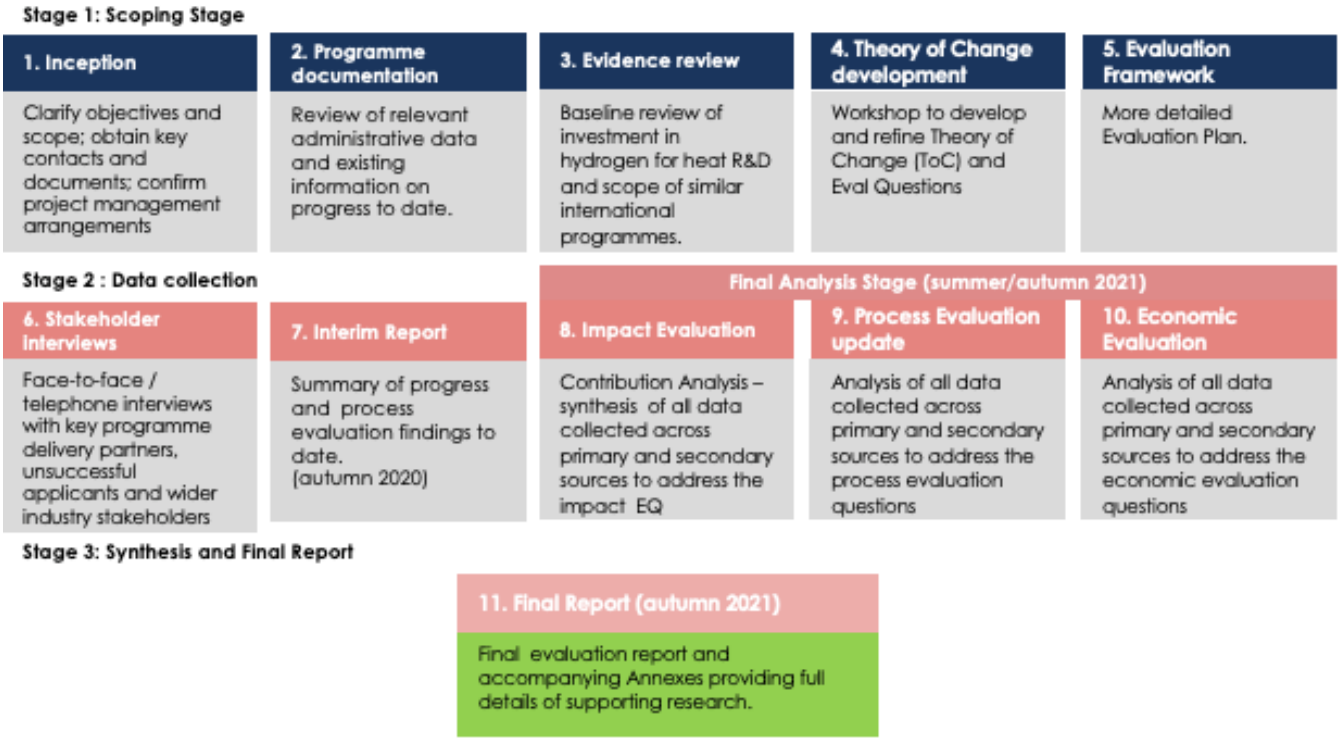
7. How has the programme achieved these impacts?
8. How effective and efficient has the programme delivery plan been?
9. What is the overall cost-effectiveness of the programme?
10. What is the wider learning from the evaluation for DESNZ?

Methods

The evaluation took a mixed-method, theory-based approach. Specifically, a Contribution Analysis with Process Tracing, to assess the contribution of the programme towards meeting its intended outcomes and impacts, with an economic Cost Effectiveness Analysis alongside this. The evaluation included research interviews with Hy4Heat contractors, DESNZ officials, regulatory bodies and external gas stakeholders. It also drew upon analysis of a wide range of secondary data sources including; programme documentation, an international literature review of hydrogen heating programmes, hydrogen strategy policy documents and analysis of databases on patents and hydrogen investment trends.

Figure 2 below provides an overview of each stage of the evaluation and the methods used. Annex A: Evaluation Plan and Methods, provides a more detailed description of the methods used, whilst this section provides a brief summary.

Figure 2: Summary of evaluation workplan. Green denotes current phase



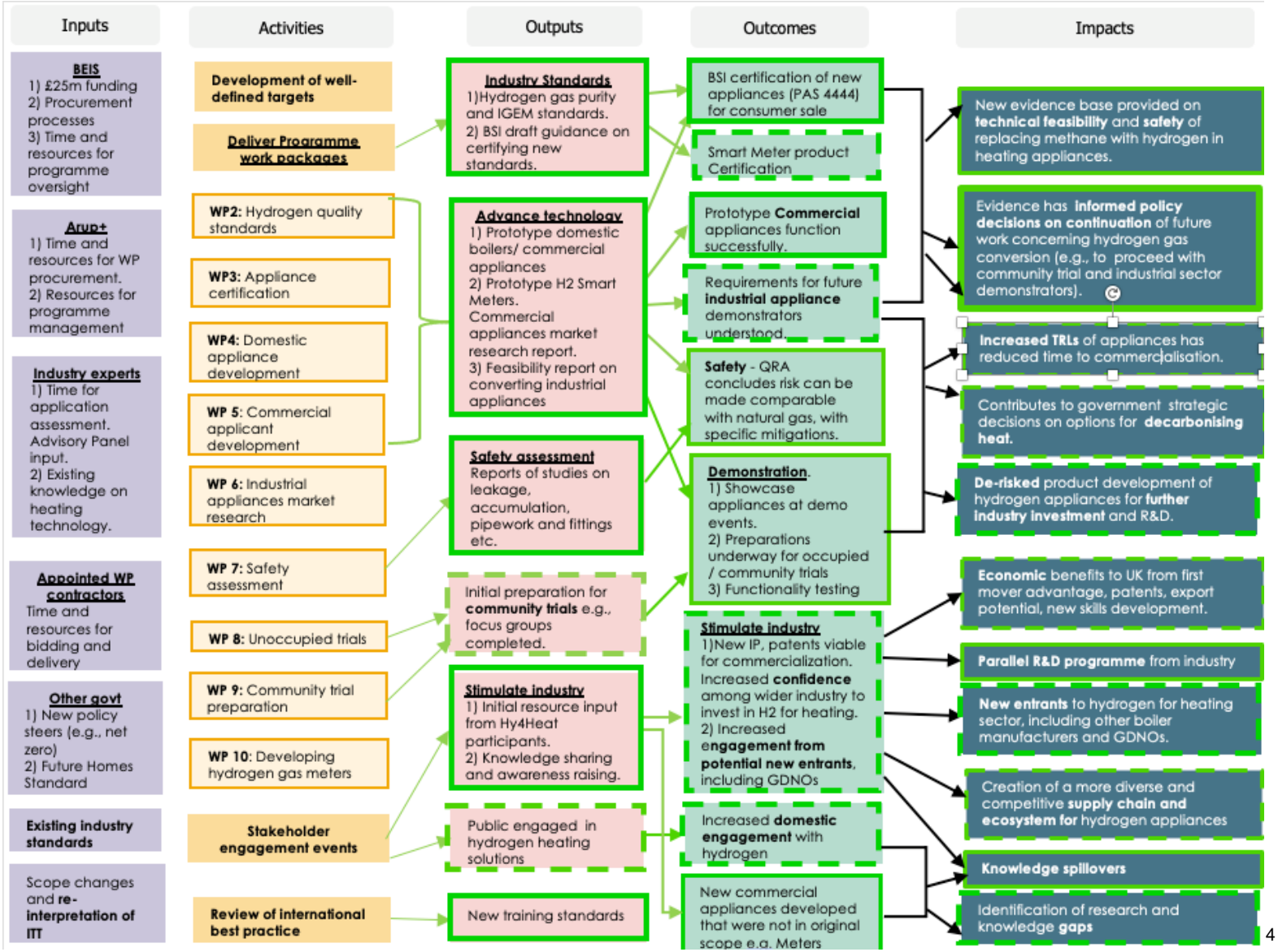
Impacts of Hy4Heat

Theory of Change

An initial pre-fieldwork Theory of Change (ToC) for the Hy4Heat programme was developed as part of the project scoping stage. Reviewing the Logic Model provides a useful tool for mapping the extent to which Hy4Heat has delivered against the expected outputs, outcomes and impacts envisaged in the pre-fieldwork Evaluation Plan (Annex A). Figure 3 below provides the Logic Model, with the following colour key to summarise progress:

- Boxes highlighted with a solid green outline note outputs and outcomes that have already been achieved, at the time of writing
- Boxes highlighted with dashed green outlines note outcomes that are beginning to emerge but not yet fully achieved. These are not intended to highlight WPs that are failing to deliver, acknowledging that some WPs are yet to complete or have been reprofiled
- Boxes highlighted in red mark any outcomes that have not been achieved or are not beginning to emerge. As Figure 3 shows, there are no outputs, outcomes or impacts in this position – all have been achieved or are at least emerging.

Figure 3: Hy4Heat Logic Model

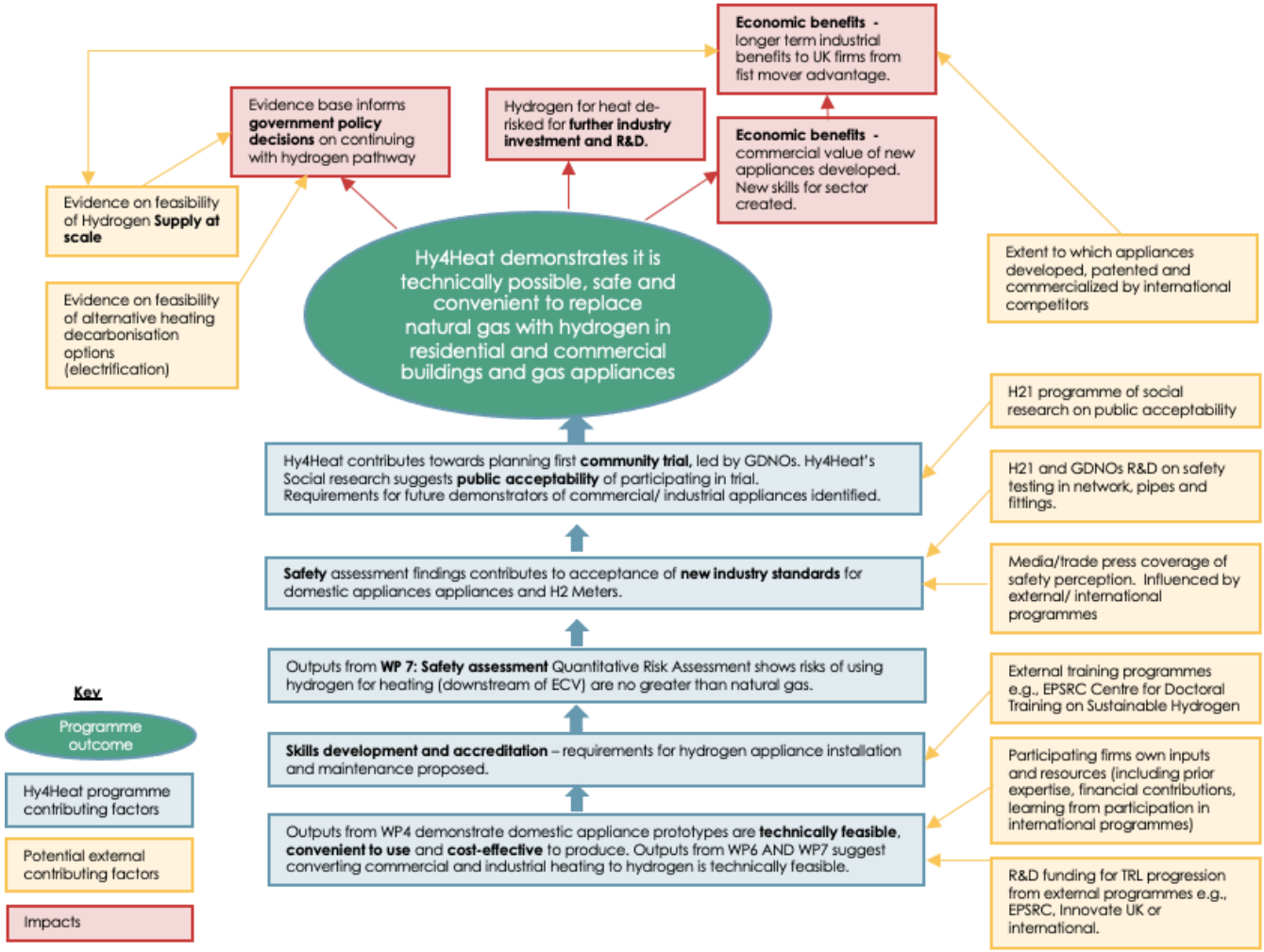


[4]

[4] BEIS changed its name to the Department for Energy Security and Net Zero (DESNZ) in February 2023.

The Logic Model formed the basis for developing a refined ToC, which illustrates the potential role of external factors in contributing towards expected impacts, as provided below. Annex D provides a more detailed description of specific contribution claims that were tested to assess the ToC, plus results of Process Tracing tests to assess the strength of evidence in support them.

Figure 4: Hy4Heat Theory of Change: Potential role of external contributing factors



Outcomes and Impacts

This section provides an assessment of progress made by the programme towards the intended outcomes and impacts outlined in the Theory of Change.

Development of hydrogen heating appliances

A core aim of Hy4Heat was to develop a range of new, first-of-a-kind (FOAK) heating and cooking appliance prototypes. The main Work Packages (WPs) focused on appliance technology development included:

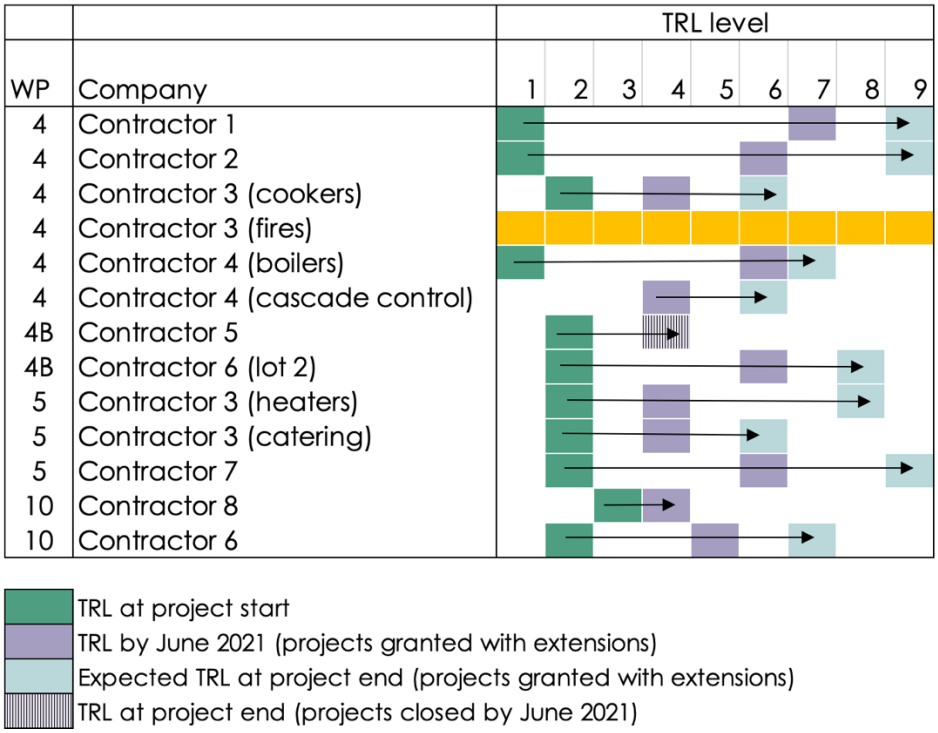
- WP4 - development of hydrogen boilers, cookers and fires for use in domestic buildings.
- WP4b development of a range of ancillary components such as control valves and excess flow valves, needed for the safe installation of hydrogen appliances.
- WP5a - a market research study into the variety of commercial appliances and the issues to be addressed in their conversion or replacement with hydrogen appliances
- WP5b– development of heating and cooking appliances for use in commercial settings, such as catering equipment and boiler cascade systems.
- WP6 - a market research study into the variety of industrial appliances and the issues to be addressed in their conversion or replacement with hydrogen appliances.
- WP8 demonstration facilities - two semi-detached houses have been built in Low Thornley, Gateshead, in partnership with gas distributors Northern Gas Networks (NGN) and Cadent. The demonstration houses, referred to as the "Hydrogen Home", showcase the functional performance of domestic boilers, hobs, cookers and fires prototypes developed through Hy4Heat in a realistic domestic setting.
- WP10 – development of hydrogen smart meters.

Evidence gathered from interviews and a review of programme documentation suggests Hy4Heat has successfully developed a range of functioning appliance prototypes to demonstration phase. Analysis of DESNZ Energy Innovation Portfolio (EIP) KPI data[5] for Hy4Heat was undertaken for KPI 5 "*Technology Readiness Level (TRL) at the start, currently and at project end*." SICE KPI data under KPI 5 (TRLs) provides an indication of current development of technologies by Hy4Heat contractors in terms of Technology Readiness Levels. TRL data are only available for three work packages – 4, 5 and 10. As shown in Figure 5 below, most of the technologies developed in these work packages were starting from a low base of technology development - being at TRLs 1 (Basic Principles) and 2 (Invention and Research).

As shown in Figure 5 below, almost all the appliance developers expected to have developed their technologies to prototype or demonstration level (TRL 6-8) by the end of the programme.

[5] There are 9 SICE KPIs in total, covering a range of topics including; estimates of achieved energy efficiency, reduced carbon emissions and number of products sold. A guidance document on the definition of TRLs and other KPIs is provided by DESNZ to project contractors to enable them to assess progress on each. Many of the KPIs are not relevant to Hy4Heat due to appliances being at a pre-commercial stage of the TRL progression. We have only reported on KPIs in this report that were considered relevant to the evaluation questions.

Figure 5: KPI 5: Technology Readiness Level at project start, currently and at project end



Source: Technopolis, based on SICE KPI data. June 2021. Please note, the diagram is based on the latest available data and that contractors may have made further progress between then and the publication of this report.

Across all non-Hy4Heat projects in the DESNZ Energy Innovation Portfolio (EIP) KPI dataset, the mean TRL increase was 1.8, compared with 3.2 for the appliance development work packages for Hy4Heat. The TRL progression with Hy4Heat has therefore been slightly higher than across the EIP portfolio as a whole. EIP programmes support innovation across a wide range of technologies, which face inherently different challenges in their development and commercialisation, so the programmes are not directly comparable. For example, it may be more complex to advance a large Carbon Capture and Storage infrastructure project through 3 TRL levels than making similar TRL stage advancement for a hydrogen boiler. However, it does suggest that TRL advancement through Hy4Heat has made successful progress (like other projects in the EIP), especially when considering the low base of TRLs these FOAK technologies started from.

Interviews with appliance manufactures support the conclusions from the KPI data analysis. Most reported they expect their technologies to have reached at least TRL 6 (a functioning prototype) by the end of the programme. However, progress towards demonstration of protypes in a realistic setting and their readiness for commercialisation varied across specific appliances. Developers of both domestic and commercial appliances noted that further work is needed to test their products reliability and durability before they can be implemented in a demonstrator or real-life setting working 100% with hydrogen. The lack of laboratories to test appliances was highlighted by some contractors as a barrier to fully validate the technologies before they can be implemented in homes as part as a community trial. Some developers reported the only missing component for them to progress to TRL 8 is to place their appliances in a demonstrator facility.

> *"The [name of the technology developed during Hy4Heat] are ready for a demonstration project, and we wanted to be part of the WP8. We have spoken*

> *with BEIS[6] about having this product on a demonstrator site. I think that is really important that that happens. But we do not have much control over that". (WP Contractor)*

> *"There are still some tests needed before putting the products in a demonstrator of a real-life setting working with hydrogen, to know what happens when you run them for a week. Because we are using stainless steel, and I am personally a bit concerned that hydrogen and the gas burner will degrade the surface of the stainless steel. (WP Contractor)*

As noted in the Introduction Section of this report, fieldwork for the evaluation was undertaken through summer 2021, while the Hy4Heat programme was not fully complete. Whilst most appliance development contractors had achieved their key milestones on prototype development by June 2021, some had been granted project extensions to enable further testing and demonstration work until c December 2021.

Manufacturers interviewed also noted further work is needed to develop production lines in order to manufacture appliances at the scale required for a commercialisation or a large town conversion. For example, the hydrogen boilers were developed as prototypes with some new bespoke components "hand crafted" in a workshop, thus further work is needed to redesign the tools that make the components to produce at scale.

> *"The readiness of the product is quite high. The passage of prototypes to final product to be developed to mass production is easy. Of course, we need to implement all the production lines and processes but the technology we have adopted and the tests we are doing seem to say that mass production is quite near". (WP Contractor)*

The need for further investment in production infrastructure is not surprising given the current TRLs of Hy4Heat-developed appliances – most have not reached TRLs 8 or 9 which is when organisations would start to look at expanding production. Nevertheless, interviewees stated that there are no technical barriers preventing them from developing production lines for the mass production of appliances. However, to support internal investment decisions on production at scale, further certainty is needed on the market for appliances and likelihood of converting gas networks to hydrogen.

> *"It relies 100% on the hydrogen strategy and the market for this appliance. We have lively debates internally; we have to see that it's worth the investment needed to put something like this into production. From a technology-manufacturing perspective it is very feasible, as we've proven this within this project, but to invest the money in having a dedicated production line we need to see a market strategy not only from the UK market but from all markets". (WP Contractor)*

Variable progress has been made on TRL advancement between Hy4Heat WPs. WP4 (domestic appliances), has advanced the furthest; reaching live public demonstration of the functional performance of a range of heating and cooking appliances at the Hydrogen Homes demonstration facility (WP8). Prototype commercial appliances have also been developed under WP5, although respondents interviewed noted they have not yet reached the same level of testing and demonstration phases as WP4 appliances. WP6 (industrial appliances) focused

[6] The Department for Business, Energy and Industrial Strategy (BEIS) was superseded by DESNZ in February 2023.

on a market research study to assess the extent of industrial appliances that may be within scope for conversion in future, with other DESNZ programmes (as outlined below) tackling on the actual development of industrial solutions.

DESNZ officials and Hy4Heat programme management contractors interviewed explained that decisions to prioritise advancement of domestic appliances was based on pragmatic consideration of what evidence is needed in 2021, to inform design of the first community trial in 2023. The first trial will focus on converting domestic buildings within a local neighbourhood. Therefore, it was not necessary for Hy4Heat to develop a wider range of commercial and industrial appliances at this stage. In addition, other DESNZ and UKRI innovation programmes are supporting development of larger hydrogen technologies for industrial use (e.g., the Industrial Fuel Switching Competition, the Industrial Energy Transformation Fund and the Industrial Decarbonisation Challenge Fund). Wider innovation programmes will explore the development of commercial and industrial appliances to support decisions on their inclusion in a potential hydrogen town conversion trial before the decade. Hy4Heat therefore prioritised delivering evidence on "*what do we need to know now*" to meet its objective of informing decisions on progression of the first community trial in domestic buildings.

Safety of Hydrogen appliances

Some WP contractors and wider GDNO representatives interviewed felt that Hy4Heat's most important achievement has been receiving a letter of assistance from the Health and Safety Executive (HSE) confirming the relevance for trials of the safety assessment developed as part of WP7. The overall Quantitative Risk Assessment (QRA) indicates that usage of 100% hydrogen can be made as safe as natural gas when used for heating and cooking in detached, semi-detached, and terraced houses of standard construction. Several Hy4Heat work strands, and analysis of external evidence, fed into the overall QRA. These include WP7 experimental tests on the risk of hydrogen gas accumulation, leakage and ignition from using appliances and associated pipework within a building. Other WPs developed insights relevant to safety, such as LED indicator systems to demonstrate the ignition of hydrogen on gas cookers, and better understanding the need for adding odorants to hydrogen rather than colourants (WP2).

One respondent interviewed went so far as to describe the quality of the safety evidence produced by Hy4Heat, as "world leading" and stated that it is gaining interest internationally. As described in the Case Studies in Annex C, international programmes testing the safety of hydrogen for heating have focused on blending hydrogen with natural gas in gas networks (in Germany) or the implementation of a hydrogen boiler as part of a heat network to power an apartment block (in the Netherlands). However, Hy4Heat's assessment of the risk of gas leakage, accumulation, ignition and explosion from a variety of appliances within a domestic setting was reported as being first of its kind.

> *"I think it's done pretty well, to be honest. It delivered everything it set out to do. It was quite a soft announcement as well (publication of HSE's approval of the safety assessment). It was a massive milestone that this project delivered…. I think the evidence is world leading. So I speak to lots of my peers internationally, and we (the UK) are definitely in front on this". (GDNO Representative)*

However, several Hy4Heat stakeholders interviewed acknowledged that the safety assessment has some limitations. There are evidence gaps that will need to be addressed before wider conversion of gas networks can be implemented in future. It was not within the scope of Hy4Heat to cover all of the areas outlined below, however, respondents noted recommendations on evidence gaps that future R&D programmes should address.

- The safety assessment findings are not applicable to all types of domestic buildings, such as flats or multi-occupancy buildings. The safety assessment prioritised the types of domestic buildings that were considered as being likely within scope for inclusion in the first neighbourhood trial e.g., detached, semi-detached, and terraced houses of standard construction. Further safety assessments of other building types will be required if they are to be included in wider village trials and town conversion pilots in future.

- The safety of supplying hydrogen to homes via gas networks – Hy4Heat focused on the safety of hydrogen gas within buildings, downstream of the emergency control valve. GDNOs will be required to complete safety assessments on the use of hydrogen within gas networks.

- Hy4Heat involved experimental testing on the risk of gas leakage, accumulation and ignition. The safety assessment of the impact of hydrogen deflagration (e.g., the extent of damage to the fabric of buildings in the event that deflagration does occur) was modelled, drawing upon evidence from secondary sources. The model was described by some respondents as having some limitations and assumptions that will require validation through testing before decisions can be made on widescale conversion of gas networks to hydrogen. Nevertheless, the evidence has been independently reviewed and accepted by the HSE. Further experimental testing was recommended ahead of a potential conversion of a village, and then a larger town before 2030.

- Further safety certifications are needed for hydrogen meters.

- While the safety assessment has provided assurance to industry stakeholders, some respondents stated that further work was needed in convincing the general public of hydrogen's safety in order to secure participation for future community trials.

Role of Hy4Heat on informing policy decisions

A key objective of Hy4Heat was to provide sufficient evidence to inform policy decisions on whether to progress with a community trial. In November 2020, Government published "The Ten Point Plan for a Green Industrial Revolution". This provided confirmation of government's commitment to progress with trials on the use of hydrogen appliances in real domestic settings. The target milestones included in the Ten Point Plan (page 11) include:

- "By 2023 we will support industry to begin hydrogen heating trials in a local neighbourhood"

- By 2025 – "Will support industry to begin a large village hydrogen heating trial and set out plans for a possible pilot hydrogen town before the end of the decade".

The UK's Hydrogen Strategy (August 2021) affirmed the government's commitment to work with industry to conduct first-of-a-kind hydrogen heating trials in residential community settings, including a neighbourhood trial by 2023 and a village scale trial by 2025. The Hydrogen Strategy report makes reference to Hy4Heat in six places. In relation to the community trials, the report notes that Hy4Heat has developed '100 per cent hydrogen-ready' appliances and that the new Net Zero Innovation Portfolio (NZIP) will build upon this to commission further collaborative research directed towards end-users of hydrogen heating appliances to test consumer experience "following on from Hy4Heat endpoints".

A review of a DESNZ internal Business Case for approval of the full programme of work with industry on Hydrogen Heating, including consumer trials (as outlined in the Hydrogen Strategy)

was also carried out to assess whether Hy4Heat informed direction of this future work. The Business Case document references Hy4Heat in nine places. Similar to the Hydrogen Strategy report, it outlines how Hy4Heat has supported successful development of prototype appliances and that a future programme will aim to work with industry to test their implementation and usage in a community setting. Aside from the technological development of prototype appliances, the Business Case outlines a range of other Hy4Heat outputs which future programmes will directly build upon, including development of user standards, competency frameworks for gas heating engineers and safety assessments.

> *Interviewer: "I was wondering the extent to which Hy4heat contributed to that policy decision in the 10 Point Plan or was it more due to other factors…"*
>
> *Respondent: "Definitely, definitely Hy4Heat… It was Hy4Heat that showed that this was doable"*

Respondents explained that the first stage of the trials outlined in the Ten Point Plan (a 'neighbourhood' trial, by 2023) is expected to be delivered through the H100 programme[7], led by network operator SGN, with funding contributions from Ofgem and the Scottish Government. H100 aims to convert up to 300 homes in Levenmouth, Fife to hydrogen. The final decision to progress with implementation of H100, was informed by successful completion of Hy4Heat outputs, including the production of functional appliances and scrutiny by HSE on Hy4Heat's safety assessment research. As illustrated in the quote from a respondent below:

> *"H100 had a good proposal which they've been developing over a number of years, but they did not have a safety case [sic] and they weren't allowed to develop a safety case [sic] because the GDNOs are not allowed to do anything below the meter. They had no appliances, and they didn't know what adjustments they'd have to make to the houses converted to hydrogen. So Hy4Heat was absolutely key to that. And we were kept really close to H100 to make sure that that first trial happened.*
>
> *The first trial is funded by Ofgem, and the Scottish Government, which is made possible by Hy4Heat, so you can see all this is a bit of a domino effect. Hy4Heat working meant the H100 proposal was plausible, which brought in initially the Scottish Government funding and then Ofgem, and so we can then move with confidence that the trials will happen. That then gave [HM Government] the confidence to know, 'yes, I would be able to do.. a village by 2025 and a town by 2030.'" (Government official)*

Similar views were expressed by officials working in government delivery bodies involved in commissioning follow-up R&D related to hydrogen heating trials. They also noted that the safety assessment from Hy4Heat was important for progressing strands of programmes such as H100 and H21 and that certain technologies developed by Hy4Heat may be directly adopted within their programmes.

Although there was a general consensus that Hy4Heat had informed the decisions to progress with a trial, this view was not unanimous. One government official felt it was more due to 'political will' to announce progress on hydrogen rather than primarily based on results of Hy4Heat. The respondent noted that at the time of publication of the Ten Point Plan (Nov 2020), HSE's formal opinion of the safety assessment was still pending (HSE's letter was sent in May 2021). However, the same respondent did acknowledge that the development of

[7] https://www.sgn.co.uk/H100Fife

functional prototypes through Hy4Heat, as well as ongoing work to demonstrate safety, may have provided assurance and informed the decision. DESNZ officials interviewed explained that, if Hy4Heat had not successfully developed prototype appliances, or if safety testing provided evidence they were unsafe, then Government would not have been in a position to commit to working with industry to develop the community trials within the timescales outlined in the Ten Point Plan and Hydrogen Strategy.

DESNZ consultees also highlighted the alignment of the hydrogen demonstration houses (Hydrogen Home project in Gateshead, Hy4Heat WP8B, with match funding from GDNOs) with the Ten-Point Plan and the UK's Hydrogen Strategy. The demonstration facilities showcase the safe functional performance of hydrogen appliances in a realistic domestic setting. It is intended that the houses will have a minimum 3-year lifespan (potentially up to 10 years)[8] and therefore expected that during the lifetime of the houses, some of the technologies developed across Hy4Heat such as boilers, cookers, hobs, meters, and fires will be improved and may then be used in the next stage of community trials. The demonstration facilities are also intended to support public engagement and wider international dissemination in the run up to COP26 on the feasibility of the hydrogen for heating strategy.

In summary, evidence gathered strongly suggests that Hy4Heat has met its objective on informing policy on the continuation to community trials. The results of the first neighbourhood trial in turn will influence decisions on the introduction of larger scale town conversions and the direction of future R&D programmes to fill evidence gaps that need to be addressed to support their implementation. The decisions to commit to community trials were not based on the results of Hy4Heat alone, but the programme's findings that it is feasible to use hydrogen in a range of heating and cooking appliances were a key contributing factor.

The results of Process Tracing (PT) tests used to assess evidence on the contribution of Hy4Heat to informing decisions on community trials can be found in Annex D. The table below provides a summary of the results and an assessment of overall strength of evidence.

Table 1. PT tests of Contribution Claim 1: Hy4Heat informed policy decisions on proceeding with community trial

Results of PT tests	Evidence based on 'Authoritative source'?	Does evidence triangulate across sources?	Overall categorisation[9] of strength of evidence
Two Smoking Gun tests passed in favour of hypothesis. Two Smoking Gun tests of Alternative Hypotheses failed.	Yes	Yes	Strong evidence in support of contribution claim

Influencing follow-on R&D work from programme participants

Around three quarters of WP contractors interviewed stated they plan to continue working on developing hydrogen for heating solutions. In most cases, contractors explained that their work on Hy4Heat has acted as a catalyst to enable follow-up work in the sector. For example, by

[8] See https://www.gov.uk/government/news/say-hy-to-the-home-of-the-future (accessed 5 October 2021)
[9] Strength of evidence categories include: 1) Strong evidence in support 2) Moderate evidence 3) Mixed or weak evidence in support 4) No evidence in support of contribution claim.

undertaking follow-up R&D to develop refined versions of prototype appliances developed through Hy4Heat, or by winning contracts to support their development in other countries.

Our interviews suggest that at least four contractors have confirmed plans in place to continue work in hydrogen, having developed their own R&D infrastructure (e.g., testing facilities, new IT systems) to continue hydrogen research. Contractors are funding this activity in a variety of ways – some have funded developments form their own internal R&D budgets, while others have relied on public funding, either through new DESNZ competitions, or by contributing to existing publicly-funded programmes like H21. Contractors have given a wide variety of reasons for wanting to continue to work in hydrogen for heating. For some the decision fits with wider organisational strategic objectives centred on contributing to climate change mitigation. For others, they are now more confident in hydrogen heating becoming a viable market and therefore see it as a commercial opportunity to exploit.

> *"It is very likely we continue working in the sector. Having been involved in the programme and talking to so many different businesses and customers since we started it, we have a lot more confidence that a percentage of households will be running on hydrogen. And because of that, we want to make sure that the market that we're in, for natural gas, we are going to be in the same market for hydrogen. And right now, we are working in the area conducting the research and testing of [name of product]. We know that if hydrogen does get rolled out, we want to be part of it". (WP Contractor)*

While the vast majority of contractors are interested in undertaking further R&D work in hydrogen for domestic heating, around a fifth of interviewed contractors did allude to it still being too early to commit to longer term and larger scale hydrogen for heating R&D. For them, a clearer signal from the government is needed on committing to gas network conversion to ensure their investment in technologies do not become stranded assets.

> *"The thing that we always consider with a new development like this, is if there is a market or some sort of funding that we can use to address the issue, then yes, it is very likely that we continue working in the area. Now, we've got the technology, so we just need the market conditions. (WP Contractor)*

Stimulating industry to invest in parallel programmes of hydrogen R&D

Another of the original objectives of Hy4Heat was that it would stimulate industry, particularly GDNOs, to undertake a parallel programme of technical, performance and safety work on the distribution network. This links to work that would be required to test the use of hydrogen in the distribution network in order for a community trial and the broader conversion of hydrogen for heating to progress.

Interviews with GDNOs, gas network trade bodies, and government officials were used to assess the contribution of Hy4Heat towards meeting this objective. The vast majority of respondents provided responses indicating that Hy4Heat has had some level of impact on influencing the R&D programmes of GDNOs (See Annex D on Results of Process Tracing for details).

Many respondents commented on the collaborative working arrangements that were in place as part of the governance arrangements for Hy4Heat. This enabled GDNOs to feed in views to Hy4Heat programme management on which areas the programme should prioritise and, vice versa, for senior managers of Hy4Heat to identify any gaps in the development of technologies or components which may be within scope for GDNOs to cover in the R&D programmes they

manage. This enabled government, GDNOs and trade body representatives to take a holistic view of the hydrogen supply chain from transmission through the networks to end usage of appliances within homes, identify gaps and agree 'who does what' to address them. As illustrated by one respondent:

> *They've [name of GDNO] been doing work on the safety case [sic] upstream of the emergency control valve. So basically, safety of usage on the grid, and we're working closely with them. And they were actually putting a lot of pressure on us to get our safety case done [in Hy4Heat]. We've now done that and now they're trying to merge the two. So for me, that's been absolutely fantastic that the two groups have really been pushing each other.*
>
> *There are some things where we said we'll do this and, and you do that. A good example is the gas meter. We realised that the emergency control valves can be upstream and downstream of the meter. Initially, we naively assumed that meant we weren't doing the meters and the GDNOs were doing the meters. And the GDNOs kind of went, we're actually not doing the meters and we said, OK, we'll step in and we'll do the meters, which we've done.*
>
> *But we have had a poor response on hydrogen alarms so [name of GDNO], picked that up and then they've run a competition on hydrogen alarms. So, I think that gives a good example of how these bodies have started to collaborate and use their Ofgem funding [discretionary R&D funds, regulated by Ofgem]. They've started to use them to move things forward and then the combination of that was for us to be able to pronounce that we're ready for a trial. (Government representative)*

An example of how the results of Hy4Heat have had an impact on enabling GDNOs to progress is through HSE's formal letter of assistance in relation to the safety assessment. As one GDNO explained:

> *So where this all comes together is to have a quantitative risk assessment for all that work upstream of the house. We've got the safety evidence in the home [from Hy4Heat] and obviously the full picture is you put those two together and assess whether it is it safe overall. So that interface is the bit our programme is now addressing.*

As summarised by another respondent:

> *"The fact that HSE has validated the safety case [sic] from Hy4Heat, it means that infrastructure and deployment trials can be taken to the next level." (Industry stakeholder)*

However, one GDNO representative felt that, rather than Hy4Heat influencing the work of GDNOs, it was originally prior work of GDNOs which influenced government to commission Hy4Heat. The respondent explained the main reason they were not able to undertake R&D covering the end-to-end supply themselves was because components and appliances downstream of the emergency control valve are outside the remit of their licensing obligations.

> *Before Hy4Heat I think the networks were already doing major research programmes. Officially our licence obligations finish at the tap. Downstream of the tap, or the emergency valve just before the meter, is not really our responsibility under our licence. And so there was a gap in the market to say,*

> *well, who's actually going to co-ordinate all the downstream work? So the government decided that they were going to do it themselves. And that is how Hy4Heat got setup".*

Nevertheless, this respondent did also acknowledge that the findings of Hy4Heat will enable networks to progress with a community trial. They also commented on the collaborative working arrangements between GDNOs and DESNZ as being a positive aspect of programme design. WP8 to develop the demonstration homes was cited as an example, given it is a three-party agreement between DESNZ, Northern Gas Networks and Cadent, with all three partners contributing funding.

Stimulating wider external industry hydrogen R&D, including new entrants

Beyond the GDNOs, there is some evidence that Hy4Heat has encouraged R&D activity among wider industry. Two major UK boiler manufacturers, Ideal and Vaillant, have publicly committed[10] to developing hydrogen boilers despite not having participated in Hy4Heat. Indeed, some respondents felt these manufacturers have accelerated R&D activity in order to catch up with the progress made by Baxi and Worcester Bosch via Hy4Heat. In other instances, Hy4Heat contractors noted they have been approached by appliance manufacturers that had not directly participated in Hy4Heat to collaborate and support their future R&D activity.

There is also evidence of Hy4Heat having encouraged R&D work by international stakeholders. Some Hy4Heat contractors (including members of the Arup+ consortium, and four WP contractors) discussed how colleagues from their international divisions have approached them for insights from Hy4Heat to help inform future work. Respondents noted that delegates from hydrogen R&D programmes in Australia and the Netherlands in particular have been in close contact with Hy4Heat contractors, using knowledge gained through Hy4Heat to help progress R&D activity in their own countries. Furthermore, some WP contractors whose companies are part of a larger international group explained how Hy4Heat is influencing the direction of R&D of their sister companies in other countries.

> *"We are part of a bigger international group [name of company] and one of the other areas of the group is specialised in heating systems. That department is now also working and experimenting with hydrogen. Hy4Heat has created a bridge between those two divisions. Because before hydrogen was put on the table, we were not dealing between each other at all". [WP contractor]*

> "*We operate R&D as a global function. So we've got R&D centres in a number of European markets. Hy4Heat for us has being really good from a political point of view. It shows UK government commitment to developing hydrogen as a future option and that's given us confidence to start to look at wider development. We're developing commercial boilers to be hydrogen ready, and also looking at hydrogen for things like combined heat and power. Hy4Heat has allowed us look at the real physical, practical stuff happening on the ground, which has given us that bond to really kick start those other programmes" [WP contractor]*

Nevertheless, that is not to say that the level of parallel R&D activity has been extensive so far. Interview evidence has highlighted that even with the traction that Hy4Heat has had, there is still a certain reluctance by some parts of industry to undertake parallel R&D activity at scale. For boiler manufacturers, until there is more certainty over whether heat pumps or hydrogen

[10] https://www.vaillant.co.uk/for-installers/business-support/industry-drivers-and-legislation/hydrogen/

will play the biggest role in decarbonising heat in buildings, there is unwillingness to invest in hydrogen. Levels of R&D activity in gas hobs and gas fires will similarly largely be driven by consumer demand which, at present, remains uncertain. That said, Hy4Heat has supported initial development of hydrogen appliances, which has stimulated interest and informed the direction of R&D of external organisations.

Another indicator of increased investment in the wider hydrogen technologies sector is to assess equity investment trends. As shown in Section 3 (Value for Money), Pitchbook data was used analyse trends in firms that are developing hydrogen technologies receiving equity investment, and the value of deals. Between 2010 and March 2020 (the baseline period), Pitchbook data recorded 11 investment deals in the UK for firms developing hydrogen technologies, with a total value of $7.4 million. However, between March 2020 and September 2021, there has been a recent increase, with 15 additional deals worth $32.6 million in total. In the space of 18 months therefore, the value of deals have increased over four times the amount than it did over a ten year period between 2010 and 2020. This increase cannot be directly attributed to Hy4Heat but indicates that investment in the wider hydrogen sector is increasing.

Analysis of patent data (using PATSTAT, See Annex C for details) shows that the number of new patents filed per year for heating technologies using hydrogen has increased substantially over the last five years (both for patents filed in the UK and globally). The analysis of PATSTAT found no direct links between companies filing patents and the companies contracted by Hy4Heat. However, there is a time lag between filing a patent and having it approved for publication (up to 18 months). As Hy4Heat has not yet completed (at the time of writing) this may in part explain why no new patents linked to the programme have yet been published. Nevertheless, the patent trends provide another indicator of increased interest in the development of hydrogen heating technologies, internationally. Subsequent to the evaluation interviews, correspondence with Hy4Heat WP contractors shows that that some have recently filed patents directly relating to their work in the programme. These patents are currently pending and are expected to be published in due course.

It is evident from the interviews conducted with the programme's stakeholders, managers, and contractors that across the government and industry, there has been increasing awareness of hydrogen's potential to contribute to the UK decarbonisation strategy. The hydrogen for heating sector has become more developed, with new entrants (both in the UK and internationally) displaying commitments to develop hydrogen technologies.

Based on interview findings, it appears that Hy4Heat has played a contributing role in encouraging the development of a wider hydrogen for heating supply chain. The evidence generated by the programme has helped create more confidence in the use of hydrogen, both from technical viability and commercial viability perspectives, meaning that there is now greater willingness for potential entrants to consider working in the sector. Indeed, consultees highlighted that Hy4Heat's findings have helped stimulate interest in hydrogen solutions from non-UK organisations.

> *¨Hy4Heat has contributed [referring to the progress of the sector in the last two years]. We are an international company - we work with multiple countries and every time we mention that we are part of Hy4Heat everybody is interested to hear more about it. Also, most of the organisations within which we have discussed the topic of hydrogen they already know about Hy4Heat and are really interested in the project¨. (WP Contractor)*

Other appliance manufacturers similarly reinforced the notion that while still nascent, new entrants are taking an interest in hydrogen for heating technologies and a more extensive supply chain is beginning to emerge.

> *"What we found was that during this time [of Hy4Heat programme] our suppliers are moving on the hydrogen theme. At the beginning when we wanted information on hydrogen or hydrogen compatibility, it was a new question for our suppliers. Now something is changing, they have started working on hydrogen field. In the market, we can easily find products such as valves which are certified for hydrogen, but years ago it was impossible. So, there is more attention and interest in this kind of declaration from supply chain". (WP Contractor)*

As mentioned above, there have also been some international knowledge spillovers - with international gas network authorities and industry representatives engaging with Hy4Heat contractors to understand best practice in developing hydrogen heating systems.

Summary of Process Tracing results: Stimulating wider hydrogen R&D

To draw conclusions on whether Hy4Heat has met the intended impacts in the ToC of contributing towards stimulating industry to undertake parallel programmes of R&D, we triangulated evidence drawn upon interviews with a range of stakeholder groups and analysis of secondary data sources. The sources of evidence were used to form distinct Process Tracing (PT) tests based on the types of evidence we would expect to observe to support/refute the contribution claims. The table below summarises the results of the PT tests and overall assessment of the strength of evidence. Overall, across the evidence sources gathered, there is strong support for the claim that Hy4Heat has contributed towards stimulating industry to consider, prepare, and undertake wider programmes of hydrogen for heating R&D. The clearest example is through contributing towards the H100 neighbourhood trial in Fife, where it is expected that appliances developed through Hy4Heat will be adopted.

Table 2. PT tests of Contribution Claim 2: Stimulating wider hydrogen R&D

Results of PT tests	Evidence based on 'Authoritative source'?	Does evidence triangulate across sources?	Overall categorisation[11] of strength of evidence
Hoop test passed. Two Straw-in-the-wind tests passed. One Straw-in-the-wind test was inconclusive.	No - primarily interview findings, although supported by industry led publications.	Yes	Strong evidence in support of claim Hy4Heat contributed to influencing GDNO R&D programmes. Mixed evidence it has led to stimulating international opportunities.

Suggested future research on hydrogen for heat R&D

While it is clear that Hy4Heat has generated extensive new knowledge both for programme contractors and the wider community, it has understandably not filled all knowledge gaps around hydrogen usage for domestic heating – something which may create opportunities for

[11] Strength of evidence categories include: 1) Strong evidence in support 2) Moderate evidence 3) Mixed or weak evidence in support 4) No evidence in support of contribution claim.

new entrants. Hy4Heat has also revealed some new knowledge gaps that were previously unknown or unaccounted for at the start of the programme. The following are most notable knowledge gaps which still exist, and which will require future R&D activity to address. These include:

- A lack of standards for hydrogen use in commercial appliances
- More thorough standards needed for excess flow valves
- How hydrogen operates in flats and/or multi-occupancy buildings
- More tests about the risk and consequences of ignition that may arise from installation of hydrogen domestic and commercial appliances
- A need to look in more detail about how to bring hydrogen into home, and ensuring a joining up of upstream and downstream elements
- Processes required to scale up and automate the manufacturing of appliances.

Programme KPI data on formation of new business relationships

The DESNZ EIP team Key Performance Indicators (KPIs) data provides information of progress against indicators of certain outcomes across all programmes commissioned under the Energy Innovation Portfolio. We have analysed KPI 4 data, relating to the "*number of active business relationships and collaborations supported (formal[12], informal[13] and new[14])*" relating to Hy4Heat. The data show that Hy4Heat contractors have engaged in knowledge sharing with industry and the wider research community. Some of these collaborations have been with organisations that Hy4Heat contractors have not previously worked with.

Analysis of returns for KPI 4 shows that, amongst appliance development contractors, companies on average established 3 new business relationships as a result of the programme. These were made up of relationships with suppliers, testing and test facilities contractors, administrative relationships and technical/research partners. The company reporting the highest number of new relationships established through delivery of their WP reported 13 new business relationships overall. Only two companies reported not having established any formal or informal collaboration nor having created any new relationship during the project.

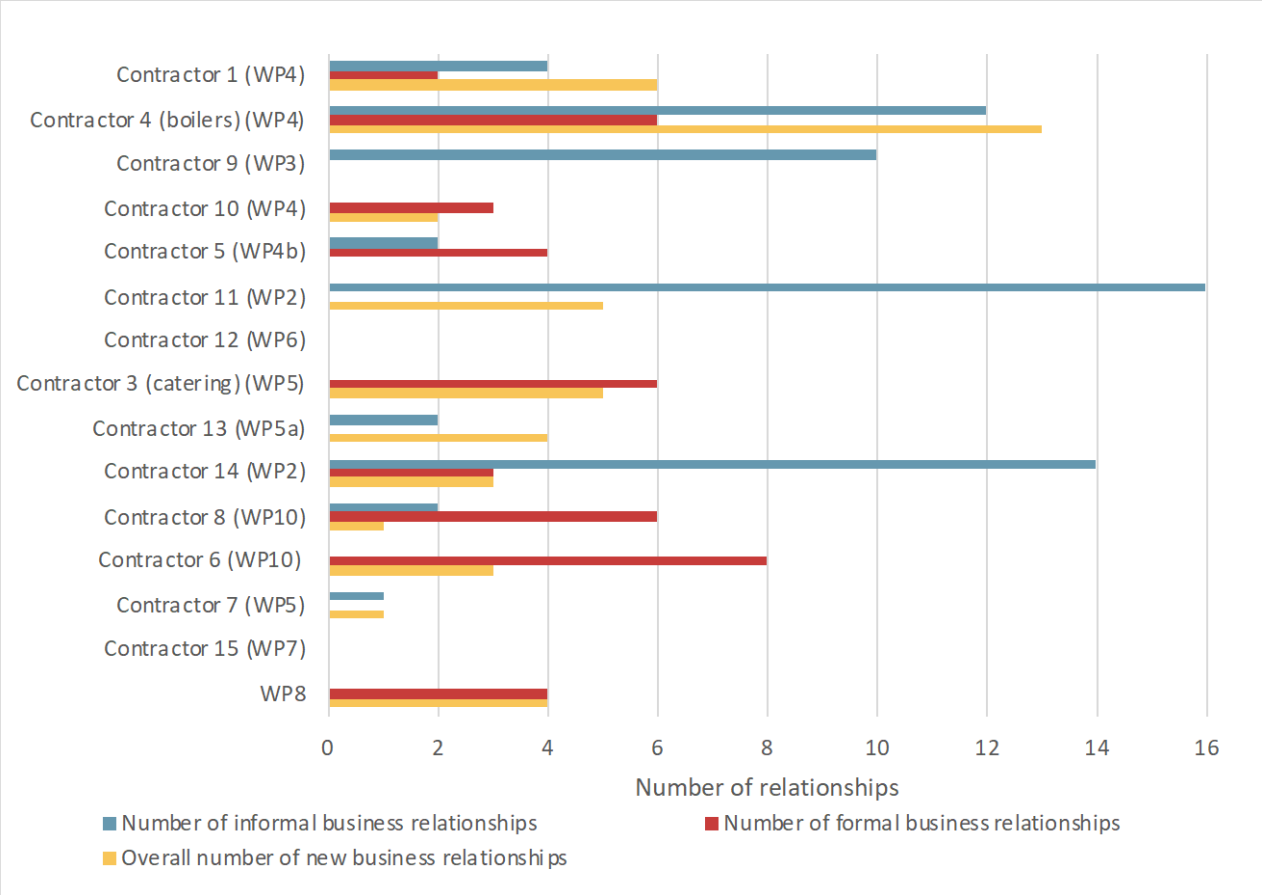
Ten companies reported informal business relationships being established through delivery of the project, with one company reporting 16 informal relationships. Informal relationships were reported as being established with following types of stakeholder organisations: GDNOs, other industry stakeholders, trade bodies, Universities, potential test facilities and expert advisors.

[12] Formal relationships and collaborations are defined as a company or organisation brough on board in a formal contractual capacity (including those in receipt of monetary payment) to deliver the project, such as subcontractors

[13] Informal relationships are defined as ones that are not contractual, but where is a partner is used in an advisory or joint delivery capacity, with substantive contribution to the project e.g. academia, advisory board members, supply chain partners, trade bodies and includes existing and new relationships

[14] Related to new relationships formed with companies that contractors had no prior engagement with.

Figure 6: KPI 4: Number of formal, informal and new business relationships



Source: Technopolis, based on SICE KPI data. June 2021.

Interview evidence provides further detail on the nature of some of the collaborations and knowledge exchange that have been occurring. Three contractors spoke of having developed relationships with the GDNOs who may have been interested in the outputs from multiple work packages, particularly to help inform demonstrations and community trials.

> *"We are looking for a lot of hydrogen networks at the moment and how you can understand how best to distribute hydrogen to a wider number of users. So we are working with all the UK gas distribution companies. And Hy4Heat has supported all of that, our understanding and the learning that we have had from the programme. Also, we are hoping to continue our work and interaction with ISO [International Standards Organisation] for the development of international standards". (WP Contractor)*

Economic benefits to UK firms from first mover advantage

Evidence from interviews suggest that, through the creation of First-of-a-Kind heating and cooking prototype appliances, Hy4Heat has raised the potential for the UK to gain a first mover advantage with respect to hydrogen for heating solutions (assuming other countries follow a hydrogen conversion pathway). Representatives from other countries were reported to have approached Hy4Heat contractors to draw on their expertise. In essence, it appears that some other countries are seeing the UK as leaders on developing hydrogen heating appliances and safety testing. As previously mentioned, a few UK-based Hy4Heat contractors stated that their non-UK sister offices have sought advice from them for their own hydrogen R&D activity. Also, representatives of an Australian R&D programme visited the UK to learn more about Hy4Heat,

recognising that the UK has particularly relevant knowledge and expertise on hydrogen heating systems.

> *“Hy4Heat has been an enabling project, helping put the UK in a good position in relation to hydrogen for heating solutions. Other countries are looking to see what progress the UK is making and using this to influence their own plans. For instance, standards agencies in Australia have been engaging with Hy4Heat and us to help inform their own decisions”. (WP Contractor)*

However, there is little evidence to date that the UK has derived much in the way of tangible economic benefits from this potential first mover advantage. In large part, this is because there are relatively few countries are actively progressing the use of hydrogen for domestic heating. As such, there are relatively few international opportunities that UK Hy4Heat contractors have yet been able to exploit.

> *"It is too early in terms of revenue and turnover, but we have potential customers certainly. We are having internal discussions about the future of research on hydrogen in our company and had it not been for this project, we probably wouldn’t be having those types of discussions". (WP Contractor)*

In some cases, Hy4Heat contractors have spoken of there being potential international markets that they can move into, but that there have also been unexpected barriers in accessing them. One appliance developer said that they had an Australian client interested in their work, but pandemic travel restrictions were making it difficult to finalise the deal. The consultee added that COVID-19 travel restrictions have meant that possible European clients have also been more interested in examining European solutions and technologies which are easier for them to view in person.

Nevertheless, one contractor noted they had already been able to generate some international sales as a result of their Hy4Heat work. Providing examples of their work on Hy4Heat was used to demonstrate relevant expertise when bidding for the contract. The respondent noted they had some already achieved some small commissions in both Australia and the United States. International market opportunities like these may also emerge for other work package contractors if interest in hydrogen heating solutions grows outside the UK.

Investment trend analysis supports the idea that while the UK has not yet gained large scale economic benefits from first mover advantage, there are some tentative signs of progress being made. As indicated in Table 3 below, between 2010 and 2021, Europe saw 111 completed investment deals in areas relevant to hydrogen for heating. Of these, the UK had marginally the highest number of deals with 26 (23%), being closely followed by Germany with 24 (22%).

However, relative to the baseline figure (2010 – 2019) where the UK accounted for 34% of the total number of deals and Germany accounted for 22%, it may indicate that the UK’s position in hydrogen for heating investment may be weakening. Analysis of the value of investment deals offers a different perspective, however. At the baseline position, the UK accounted for 5% of the total value of all European deals, while most recently, it has accounted for 22%. While Germany still accounts for the largest proportion of the total European value of deals (32%), there are some signs that the UK’s share is increasing. The data therefore reinforces the notion that first mover advantage has not given the UK a clear-cut economic advantage relative to other countries, but that it is perhaps helping keep the UK competitive against some performance indicators.

Table 3 Deals by European country for hydrogen for heat specific deals (2010 – 2021)

Country	Number of deals	Total deal size ($million)	Size per deal ($million)
United Kingdom	26	7.42	2.5
Germany	24	73.2	5.2
Denmark	15	44.1	1.0
Netherlands	11	0	0.8
Other countries	35	66.6	3.0

Source: Pitchbook, September 2021

Value for Money

This section presents the key findings of the Value for Money (VFM) assessment of the Hy4Heat programme. It follows the National Audit Office (NAO) 3E's[15] approach to assessing value for money of government spending, i.e., the optimal use of resources to achieve the intended outcomes:

- Economy: minimising the cost of resources used or required (inputs) – **spending less;**
- Efficiency: the relationship between the output from goods or services and the resources to produce them – **spending well**; and
- Effectiveness: the relationship between the intended and actual results of public spending (outcomes) – **spending wisely**.

This VFM assessment utilises findings from the primary qualitative research interviews with Hy4Heat contractors and wider industry stakeholders, as well as analysis of programme management information and secondary data sources, including Pitchbook and Gateway to Research. Further details on the rationale for using the 3E approach and data sources used can be found in Annex A.

The research team explored in detail the feasibility of undertaking different approaches to a Value for Money assessment, including a Cost Benefit Analysis and Cost Effectiveness Analysis. However, due to the types of outcomes achieved by the programme (which come before achieving economic and environmental benefits), and a lack of available data, these approaches were not utilised.

Economy

The NAO approach to assessing value for money defines 'economy' as being the minimisation of the costs or resources used to deliver a programme. The costs for the Hy4Heat programme are detailed in the table below, with a total cost[16] of £18.3 million to date (as of 28/10/2021): It is expected that approximately £22 million will be incurred at programme completion.

Table 4 Cost of the Hydrogen 4 Heat programme

Work package	Delivery included in cost	Cost (£)
WP1: Programme and technical management, safety assessment incl summary reports	Project management and safety assessment	6,390,900
WP2: Hydrogen Quality standards	IGEM, DNVGL, SGN	655,300
WP3: Appliance certification	BSI	145,000

[15] https://www.nao.org.uk/successful-commissioning/general-principles/value-for-money/assessing-value-for-money/

[16] All cost figures are in nominal prices.

WP4: Domestic appliances WP4b: Ancillary Components	All WP4 contracts	WP4: 4,890,400 WP4b: 221,000
WP5a: Commercial Market Research Study WP5b: Commercial appliances	All WP5 contracts	WP5a: 222,900 WP5b: 1,787,200
WP6: Industrial appliances	EE	185,100
WP7: Safety assessment commissioned studies	Steer, DNVGL (three lots), HSE review	916,500
WP8A: Demonstration facilities WP8B: Hydrogen Home	Demo facilities & expenses, Hy Home	280,000
WP9: Community trial preparation	Included in costs for WP1	-
WP10: Developing hydrogen gas meters	Pietro Fiorentini, MeterSit	1,098,500
Additional managed projects	IGEM, EUS, BSI	375,400
Hydrogen Heating Team projects	Arup, Mott McDonald, HSE Hydrogen Grid	985,900
Total cost[17]		£18,154,100

Source: Hy4Heat internal records, 28 October 2021

Delivery partners and wider stakeholders were asked about the costs of delivering the programme. The general consensus among stakeholders (including WP contractors and wider sector stakeholders) was that the programme was delivered at an appropriate level of cost, and that if each of the work packages had been undertaken by the private sector the private sector organisation would have incurred similar costs to deliver each WP.

The only concern raised about the cost of the programme was around the proportion of budget allocated to WP1 for Programme Management Contractors (over £6 million). Some noted that if the programme was managed directly by DESNZ, a portion of this budget could have been allocated to advance a wider range of technologies. However, it should be noted that the role of WP1 was wider in scope than solely programme management and included sourcing expertise to advise DESNZ on technical matters across a range of WPs, plus leading analysis and reporting for the Quantitative Risk Assessment and safety assessment, and incorporates the cost of WP9 on managing initial research to prepare for a community trial.

The majority of stakeholders felt that the programme management was of a high quality and delivered at an appropriate cost, particularly given the scale of the programme and the wide variety of work packages that required monitoring and risk management. A small number of stakeholders felt that the management could have been achieved at a lower cost or been more effective if DESNZ had managed delivery through direct engagement with GDNOs, with the GDNOs sub-contracting work packages. However, other stakeholders felt that due to the scale and complexity of the programme, a contractor with a reach across many industries and with

[17] This excludes the £152,400 costs for the Hy4Heat evaluation

the experience of delivering multi-strand programmes with many delivery partners was most appropriate.

It is challenging to benchmark the costs of the Hy4Heat programme against other interventions, to identify whether the costs were appropriate. This is because there are no directly comparable schemes for many of the work packages.[18] The Energy Entrepreneurs Fund (EEF) provided grant funding to businesses with early-stage clean technology products to advance the product (alongside providing incubation support to businesses).[19] This programme provided £72 million to 156 projects, with an average award of over £460,000. Work Packages 4, 5, 6 and 10 all funded firms to undertake R&D into early-stage hydrogen ready products, and are therefore broadly comparable to the EEF. The average value of grant funding to develop these technologies in the Hy4Heat programme was £542,700 (based on the cost of the Work Packages divided by 15 projects). This is slightly higher than the value of projects in EEF. However, EEF covers a broad range of clean technologies, some of which involve less costly R&D processes than those required to develop hydrogen products. Therefore, although the costs of Hy4Heat R&D projects are slightly more expensive than those delivered through the EEF, they can be seen to be broadly comparable in terms of overall costs. The efficiency and effectiveness of the spend (whether it was money well spent for the outcomes achieved) is discussed in the following sections below.

Efficiency

The assessment of the programme's efficiency focusses on how well the inputs were converted into programme outputs. In the case of the Hy4Heat programme, this relates to the key outputs for each work package, namely:

- the development of industry standards
- the technological advancements of appliances and meters
- safety assessment reports.

The development of industry standards and safety assessment reports

The development of industry standards and safety assessment reports were key outputs. These primarily relate to Work Packages 2 and 7, although other workstreams have also contributed to the achievement of these outputs. As highlighted in Section 2, this output has been fully achieved by the Hy4Heat programme, at a cost of £1.5 million (for WP2 and 7).[20] The qualitative interviews suggested that the process of developing the industry standards and safety reports had been efficient, with the funding being used to develop these outputs in an

[18] Ideally, the evaluation would have compared the cost effectiveness of Hy4Heat to other programmes targeting similar solutions outside the DESNZ SICE portfolio. However, there are a very limited number of comparable programmes internationally, and the research team were unable to secure metrics to calculate cost-effectiveness indicators for these international programmes. Additionally, there were limited available evaluations for programmes targeting similar technological progress outside the DESNZ SICE portfolio – this meant there was insufficient data to enable a comparison with Hyh4Heat. Therefore, the comparison exercise is limited to the DESNZ SICE portfolio.

[19] DRAFT NOTE: FORTHCOMING PUBLICATION OF EVALUATION – NOT YET PUBLISHED. SCHEME WEBSITE: https://www.gov.uk/government/collections/energy-entrepeneurs-fund

[20] This cost does not include a share of the project management costs (Work Package 1)

efficient manner – often drawing in advice from experts in heating industry trade bodies at no direct cost to Hy4Heat.

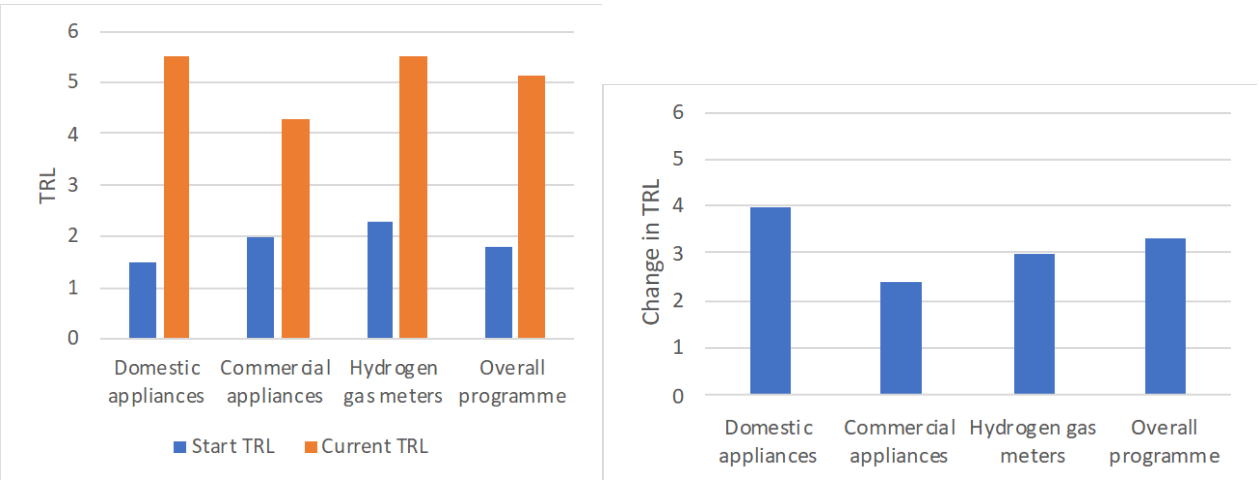
The approach taken in the safety modelling was described as being sufficiently thorough to inform risk assessment to progress with the next stage of community trials (although the progression to such a 'neighbourhood trial' will still depend on the HSE reviewing further site specific safety documentation). As noted in Section 2, some stakeholders noted that evidence on risk assessment would be strengthened with empirical testing of the impact of hydrogen explosions on the fabric of buildings. However, the modelling approach used was considered as proportionate to demonstrate an acceptable low level of risk for a neighbourhood trial, and was accepted by HSE. Further empirical testing research and risk assessment was considered to be necessary before decisions are made on converting networks to supply a larger number of homes as part of a whole town or city trial. However, this was not considered appropriate use of Hy4Heat's budget given the likely high costs and timescales involved.

There are no comparable schemes which have developed safety assessments on the risk of gas leakage, accumulation and ignition in domestic buildings from hydrogen appliances. Therefore, it is not possible to benchmark these outcomes against other programmes.

Technological advancement of appliances

Work Packages 4, 5, 6 and 10 related to the technological progress of hydrogen appliances, ancillary components and smart meter technologies. As highlighted in Section 2, the projects relating to appliance development have been successful in advancing their technologies. The average starting point and current levels for their technologies on the TRL scale are presented in the figure below, which shows that across all of the work packages firms were at a similar, very early stage of technological development. It also indicates that there has been significant progress made in the technological development of appliances through the Hy4Heat programme, with a reported average increase in TRL of 3.2 levels. As noted in Section 2, this compares favourably to the mean TRL increase across all other projects in DESNZ Energy Innovation Portfolio (1.8). Technologies in WP4 (development of domestic appliances) made the most progress, on average, progressing by four TRLs to an average TRL of 5.5.

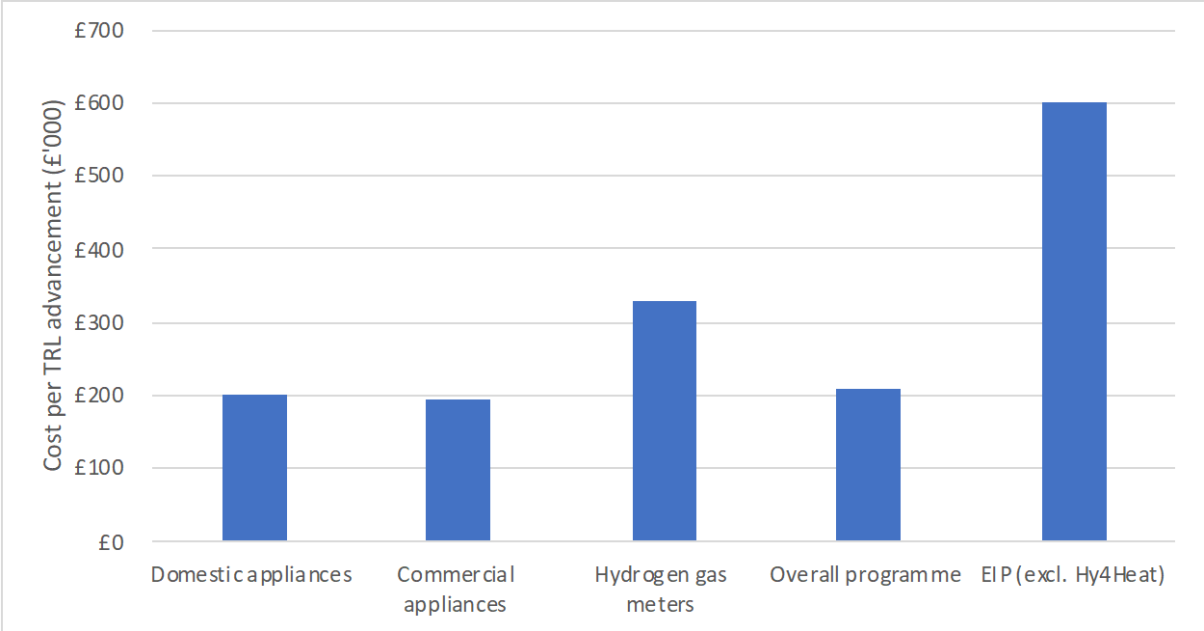
Figure 7: Average starting and current TRL by work package, and change in TRL



Source: DESNZ Energy Innovation Portfolio KPI dataset.

The cost to the public purse of the projects achieving technical advancements was reported as £9.2 million, across 13 projects.[21] This represents a cost per TRL achieved of £0.2 million. On average, the cost per TRL advancement was lowest in WP5 (just under £0.2 million) and highest in WP10 (£0.3 million), with limited variation between the work packages. This compares favourably to the cost of commensurate TRL uplifts across the wider Energy Innovation Portfolio (EIP, excluding Hy4Heat) – at £0.6 million. It is recognised that EIP covers the development of a wide range of higher cost technologies that are not directly comparable. Nevertheless, considering Hy4Heat has developed First-of-a-Kind appliances from low TRLs (1-2) to the point at which they are demonstrated as functioning successfully (including at the Hydrogen Home site Gateshead) it is reasonable to conclude this has been an efficient and effective use of spend.

Figure 8: Cost per change in TRL[22]



Source: DESNZ Energy Innovation Portfolio KPI dataset.

Effectiveness

The key outcomes outlined in the Theory of Change for the Hy4Heat programme were:

- Certification of appliances and meters (not yet achieved, pending)
- Prototype appliances function (achieved)
- Requirements for future appliances understood (achieved)
- Safety case demonstrated (achieved)

[21] The cost data used here is drawn from the project KPI reporting from summer 2021. Timescales cover the start dates of all EIP programmes since 2017 to their closure dates. All costs are in nominal prices. There are differences in the data reported here and the data presented in Table 3.1. For the purposes of the analysis here, we have used the costs as reported in the KPI reporting, as it is the same source as the changes in TRL.
[22] Costs are in nominal prices

- Stimulate wider industry to undertake parallel programmes of R&D on hydrogen gas conversion (partially achieved).

Due to the interaction of many of the work packages and the multiple outcomes they contribute towards, it has not been possible to identify a cost per outcome achieved. Therefore, a more qualitative approach has been taken to assess the effectiveness of the Hy4Heat programme.

Stakeholders stated that the outcomes of the programme had been achieved in a cost-effective manner. They suggested that in the absence of the programme, the work packages would not have been conducted in such a coordinated manner and would have taken considerably longer to achieve the same outcomes. They felt that there would have been duplication in activities, or the activities would not have been achieved to the same quality as the programme managed by bringing together all interested parties. This coordination was achieved by having a centralised programme and through engaging with all relevant organisations and businesses (for example through the steering groups), thereby addressing market barriers around imperfect information and coordination failure). Having this degree of coordination and engagement also meant that when a work package faced a particular problem which could affect its effectiveness, members of the management team could resolve the problem quickly. For example, when there was a lack of data about the number of safety incidents relating to natural gas in homes on one work package, the programme could bring together all relevant organisations (including GDNOs) and encourage them to provide the data to enable the work package to progress.

Stimulating the industry: financial indicators

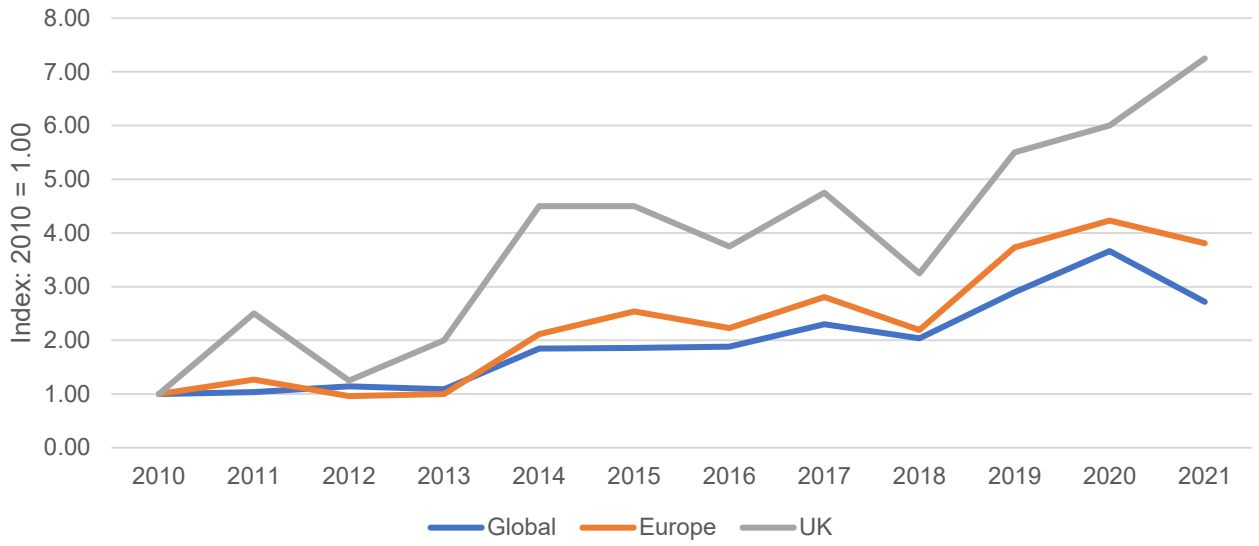
One of the wider outcomes of the Hy4Heat programme was to stimulate the wider industry to invest in hydrogen research. As outlined in Annex D on Process Tracing, there is strong evidence to suggest that this has taken place. Stakeholders stated that some of the appliance manufacturers which were not involved in the programme have since become involved in industry wide discussions around the use of hydrogen in the gas network, as a result of Hy4Heat raising the profile and possibility of the Government promoting a policy if hydrogen usage in the gas network. Some external appliance manufacturers have now made public commitments to develop their own hydrogen ready products. This was suggested to be a mechanism to maintain / exploit market position – if the Government announces a switch to hydrogen, the firms needed to have products ready to maintain their position. Additionally, GDNOs were also reported to have increased their activity in R&D in hydrogen related projects as a result of the programme (see Section 2 and Annex D). However, stakeholders were not able to comment on the value of R&D expenditure into hydrogen related projects. This indicates that the programme has been successful in leveraging further R&D expenditure and activity, although it is not possible to estimate a leverage ratio.

To further explore the wider effects of the programme on R&D involving hydrogen, an analysis of Pitchbook data was undertaken. For more details of this analysis please see Annex C, Investment Trends.

Analysis of the wider trends in global hydrogen investment, not specifically related to the Hy4Heat project, showed that there has been an increase in the number of financial deals in the UK since 2010. The number of financial deals involving companies related to hydrogen has increased from four deals in 2010 to 29 deals so far in 2021. The number of hydrogen related financial deals has increased at a faster rate in the UK than in Europe and the rest of the world, and has increased rapidly since 2018, a similar time to when the Hy4Heat programme was introduced (see Figure 8).

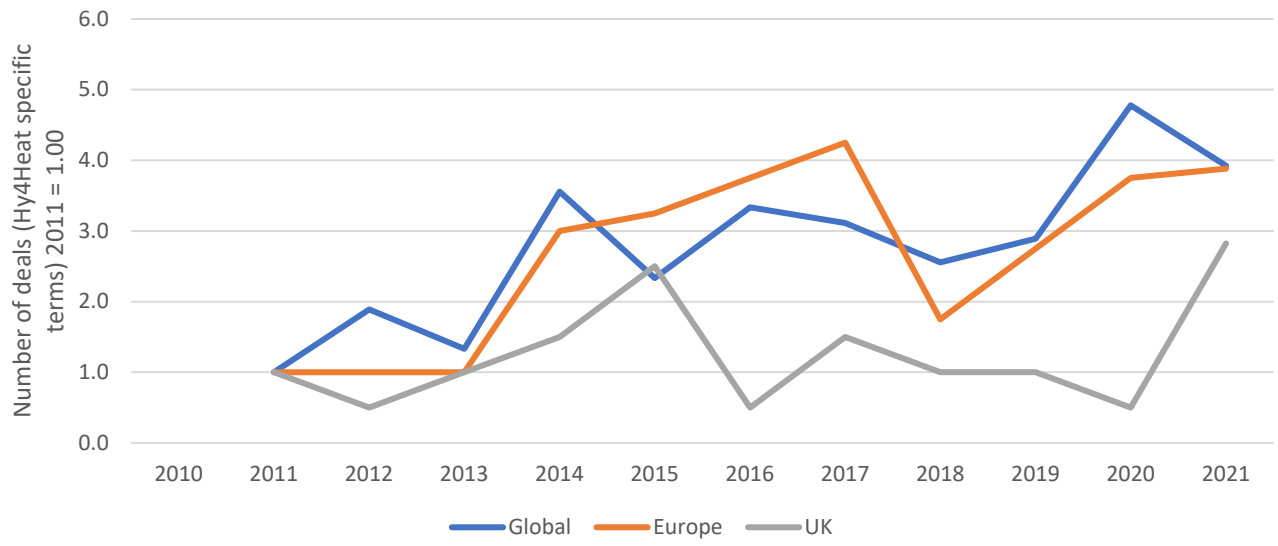
However, when the search terms were altered to only include terms relating to the Hy4Heat programme (e.g., hydrogen boilers, cookers, meters etc), there is a different pattern in terms of the number of financial deals completed. The analysis shows that in the UK, the number of financial deals completed which were covered by the Hy4Heat specific search terms fluctuated around the level achieved in 2011[23], with no sign of an increasing number of financial deals over time. This is in spite of a general increase in the number of financial deals covered by the Hy4Heat search terms at a global and European level over the same time period (see Figure 9).

Figure 7: Trends in number of Hydrogen deals, 2010 to 2021



Source: Pitchbook, September 2021

Figure 8: Trends in the number of deals for Hy4Heat specific search terms, 2010 to 2021



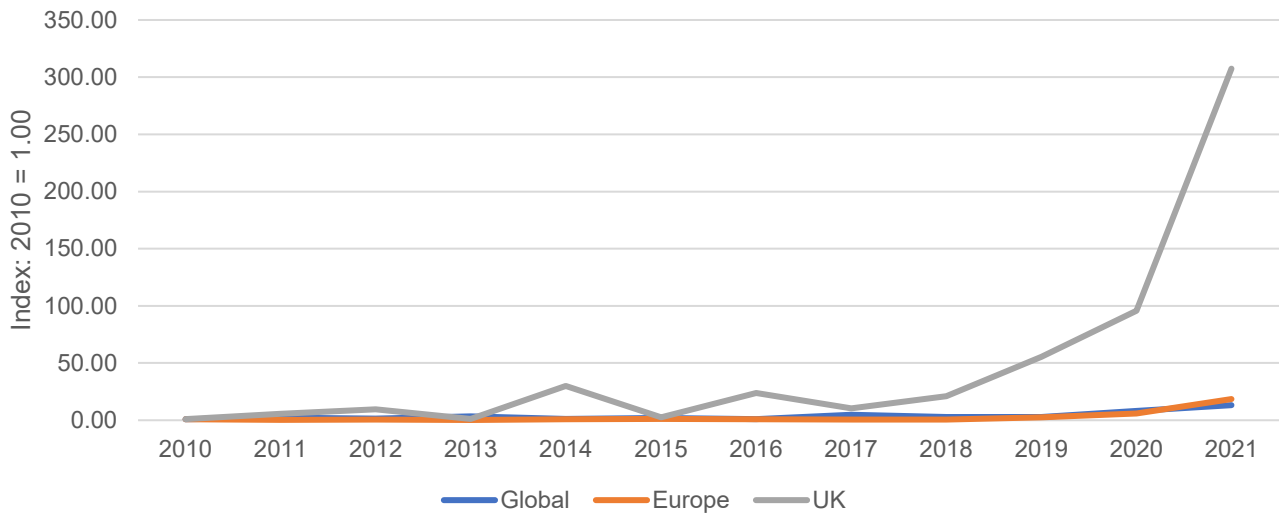
Source: Pitchbook, September 2021

[23] There were no financial deals in the UK which were covered by the Hy4Heat search terms in 2010.

A similar pattern is seen in the monetary value of the financial deals relating to hydrogen. The value of financial deals relating to hydrogen has generally increased since 2010 in the UK since 2010, with the value of deals per year particularly larger in years since 2017 and much higher in 2021 than previous years (driven by multiple multi-million dollar deals). Again, these higher financial values relate to the time period that the Hy4Heat programme has been delivered. This pattern of higher values of financial deals in the UK is more striking than the change in the value of financial deals observed in Europe and the rest of the world (see Figure 10).

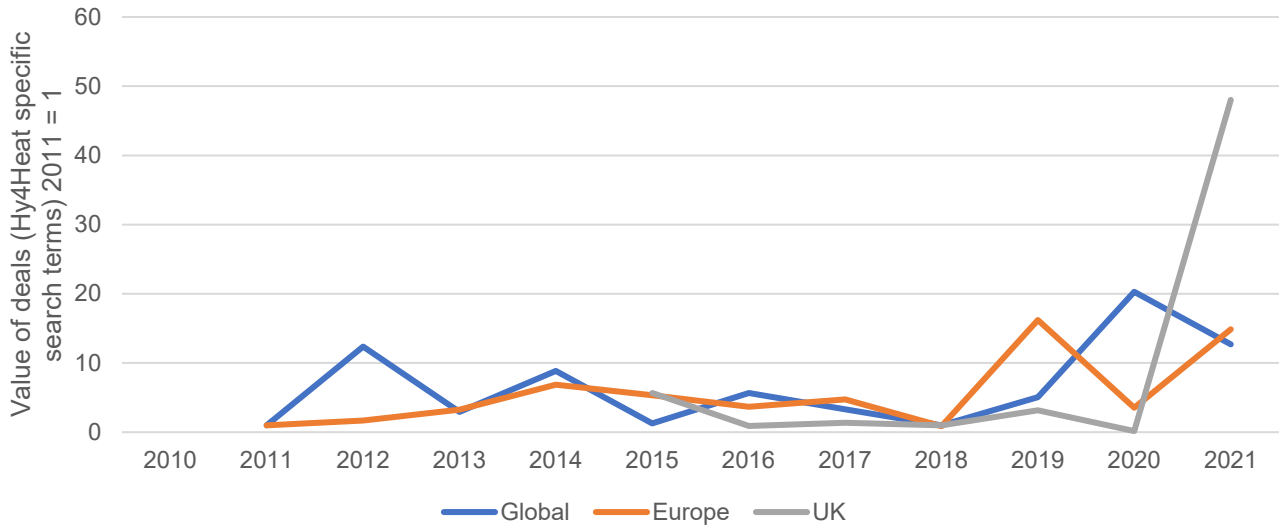
However, as with the pattern observed in the number of financial deals, the value of financial deals completed in the UK which were covered by the Hy4Heat search terms between 2011 and 2020 was not much higher than the values observed in 2011, although there has been a large increase in values in 2021, due to one large deal recently completed in the UK (see Figure 11). There also has not been a noticeable pattern in the value of financial deals relating to the Hy4Heat search terms in Europe or globally.

Figure 9: Trends in the value of Hydrogen deals, 2010 to 2021



Source: Pitchbook, September 2021

Figure 10: Trends in in the value of deals for Hydrogen 4 Heat specific search terms, 2010 to 2021



Source: Pitchbook, September 2021

Follow on funding for programme participants

The follow on funding, or additional funding secured or financial deals by the businesses participating in the Hy4Heat programme was also explored. Of the 31 private businesses taking part in the programme, Pitchbook had records for 20 (65 percent).

Most of the participating businesses had not secured any additional private funding recorded in Pitchbook. A summary of the key financial activity of the participants shows that since the programme began:

- participating businesses had merged with or acquired three other businesses;
- two companies had been acquired / bought out;
- one company had secured Venture Capital funding; and
- one participating business had secured additional grant funding.

This indicates that, in the data available for participating companies, it does not appear that the programme has had an impact on their ability to secure further funding (either equity or public funding). However, for some of the large participating companies, this would not be expected, as they would expect to fund further Research and Development activities internally.

Value for Money Conclusions

There is evidence that the Hy4Heat programme has been delivered in a cost-effective manner. The key evidence to support this conclusion includes:

- Most stakeholders reporting that the programme had been delivered at an appropriate cost
- The programme reducing potential duplication of activities, and timescales for completion, compared to if they had been delivered by the private sector in the absence of the programme
- Coordination and engagement with relevant organisations meant challenges could be overcome rapidly to allow key outputs and outcomes to be achieved
- The value of grants being made through the programme to support technical progress being broadly comparable to the wider Energy Innovation Portfolio (EIP)
- Technological progress being made at an appropriate cost - at a lower average cost per TRL increase than the wider EIP
- Qualitative interview evidence suggests Hy4Heat has stimulated increase in R&D relating to Hy4Heat. This is supported by reviews of grey literature and published commitments on websites of GDNOs and wider appliance manufacturers
- Evidence of an increase in financial deals relating to hydrogen in the UK since Hy4Heat's delivery, indicating the programme could have contributed towards increased expenditure in this area through the Government signalling an intention to introduce hydrogen-based policy measures.

Table 3. PT test of Contribution Claim 3: Value for Money

Results of PT tests	Evidence based on 'Authoritative source'?	Does evidence triangulate across sources?	Overall categorisation[24] of strength of evidence
Straw-in-the-wind test passed	No – although wide range of data sources used to draw conclusions	Yes	Moderate evidence in support of overall conclusion on good value for money. Some expected evidence was limited e.g., attributing firm level investment and patents to Hy4Heat.

[24] Strength of evidence categories include: 1) Strong evidence in support 2) Moderate evidence 3) Mixed or weak evidence in support 4) No evidence in support of contribution claim.

Effectiveness of Programme Design and Delivery Processes

Introduction

This section summarises the findings from the process evaluation focusing on the extent to which Hy4Heat's management, administrative and delivery processes have worked effectively and efficiently.

The process evaluation has been rooted in a process evaluation framework developed as part of the Evaluation Plan (and included in Annex A). The process evaluation framework set out the core process evaluation questions that the study needs to answer, while setting out the information sources that would provide the best evidence in answering these questions. Annex A provides the process evaluation framework in full but in summary, the analysis has drawn on stakeholder, contractor, and applicant interviews, plus a thorough review of programme documentation to answering the following two overarching questions:

- How effective has the organisation of contracted project management and procurement structures been?
- How effective and efficient have the internal (DESNZ and Arup+) governance and internal management structures been?

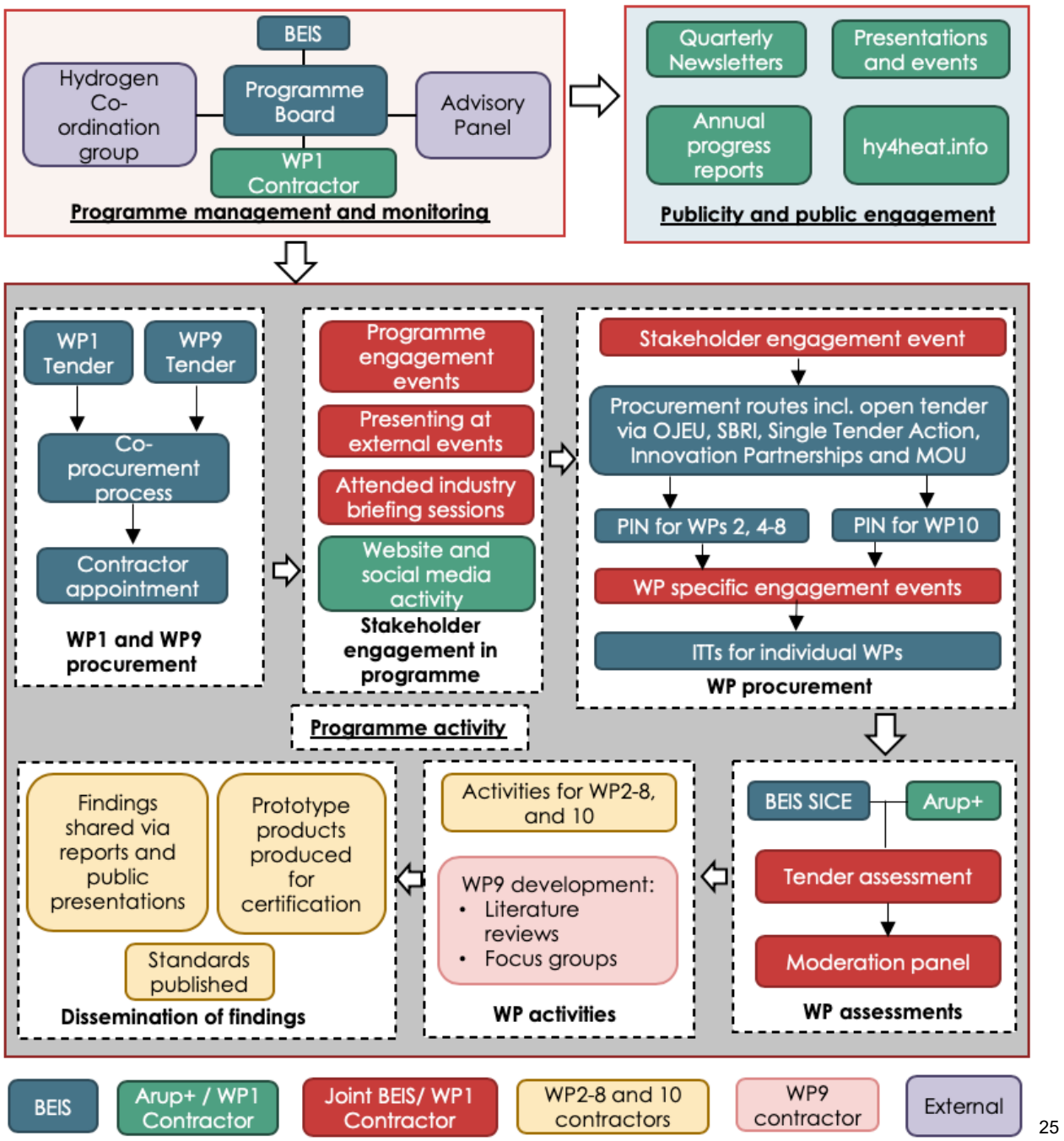
The interim evaluation report provided a detailed assessment of these two questions in the summer of 2020. It found that:

- Programme management mechanisms were largely effective. The Hydrogen Co-ordination Group and the Advisory Panel had representation from all the relevant industry stakeholders, provided good challenge to the Hy4Heat Programme Board, and their inputs led to a widening of the programme's scope
- DESNZ' management role had been well received although there were some conflicting views on the value of having a dedicated external programme manager. Some believed that in this case, Arup+ acted as an effective intermediary between DESNZ and contractors, while other felt that Arup+ provided an extra layer of bureaucracy, and meant there was no direct access to DESNZ
- Arup+ had only played a minor role in helping facilitate knowledge exchange and interactions between different work packages
- The programme's procurement processes appeared to have worked well, as did the contracting processes

For this report, we have drawn on evidence base for the interim report, plus additional evidence collected since the summer of 2020 to update our process evaluation findings.

In answering the process evaluation questions, we have considered the appropriateness and effectiveness of the different delivery, procurement and management processes that Hy4Heat has used – as summarised in the Figure below.

Figure 11: Hy4Heat programme process map



[25]

Source: Technopolis

Effectiveness of project management structures

Two parties have had project management responsibilities within Hy4Heat: DESNZ who has maintained ownership of the programme as a whole and provided expert advice and strategic oversight; and Arup+ (an Arup headed consortium which also includes Kiwa Gastec, Progressive Energy, Embers and Yo Energy), who have sought to co-ordinate activities undertaken in the majority of the work packages and assess their progress.

[25] BEIS changed its name to DESNZ in February 2023.

DESNZ

The Hydrogen Co-ordination Group and the Advisory Panel feed into the DESNZ Hy4Heat Programme Board, providing advice and challenge to the programme. The Hydrogen Co-ordination Group consisted of representatives from Gas Distribution Network Operators (GDNOs), the National Grid, IGEM, and Ofgem. The Advisory Panel brought a more diverse pool of knowledge to the programme, with members coming from industry, academic and independent experts, the Health and Safety Executive (HSE), as well as Ofgem and GDNOs. The Hydrogen Co-ordination Group and Advisory Panel were each held quarterly.

Consulted stakeholders reported that the Hydrogen Co-ordination Group and the Advisory Panel included a good representation of the right expertise and skills needed. Both groups were said to have provided useful, comprehensive advice and challenge to the programme, in particular with reviewing outputs of the WPs.

WP contractor respondents discussed how they hold DESNZ SICE technical experts in high regard and would welcome more opportunity for more bilateral discussions with them to help shape direction of individual work packages. Contractors stated that a more frequent interaction with DESNZ would have streamlined and made more efficient some processes such as changes in the WPs timelines and deliverables.

> *"BEIS[26] has some great people. They really should be working more closely with the work packages" (WP contractor)*

> *"Having BEIS involved a bit more frequently in our WP would have helped. We were just at some fundamental schedule and scope reviews which could have happened earlier. (WP contractor)*

Respondents indicated some areas of improvement for DESNZ in their management of Hy4Heat. One mentioned that for periods of time in 2021, the programme appeared to lack leadership and timescales for decision making caused some delays to projects, as a result of DESNZ internal staff changes and periods of sickness absence of key personnel. However, it was recognised that sickness leave is unavoidable, and the effects were then mitigated by DESNZ bringing in additional staff to support the programme delivery. Some interviewees also noted a perceived lack of alignment in views between different teams within DESNZ and their willingness to communicate a commitment to progressing with a community trial. However, these comments were made in interviews that took place prior to the commitments published in the Prime Minister's Ten Point Plan[27] to proceed with converting a neighbourhood to hydrogen, which may have addressed this concern.

Despite these discussions, there was a generally positive view of DESNZ's project management. Several contractors highlighted the flexibility offered by DESNZ regarding changes to the agreed timescales for delivery, particularly in the context of project delays caused by Covid-19. Some contractors interviewed also highlighted the good decision making made by both DESNZ and Arup+ during the programme lifecycle. For example, allowing the programme to take a flexible approach to identifying evidence gaps and commissioning new work packages to address them. Respondents noted this decision making and adaptive management were key to delivering the programme´s expected outcomes and objectives.

[26] BEIS was superseded by DESNZ in February 2023
[27] HM Government (2020) *The Ten Point Plan for a Green Industrial Revolution*. Available at https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/936567/10_POINT_PLAN_BOOKLET.pdf

Arup+ (WP1)

Arup+'s main responsibilities within Hy4Heat include managing work package delivery contracts, identifying and then mitigating work package risks, and monitoring milestone achievements.

Respondents discussed the merits of the governance model of having an external programme management contractor, with some difference in views. A few WP contractors, more accustomed to direct client engagement, felt this added an extra layer of bureaucracy and prevented direct access to DESNZ in advancing queries, proposing changes to project direction, and obtaining quick decisions.

> *"We spoke to ARUP+ and there are very good people across it and it's great to talk to them. But they [Arup+] are really messengers, in the sense that if you ask a technical question or a policy question, they go away and find an answer with BEIS[28]. But then you have a joint meeting with BEIS at which you get straight to the core of the issue. And I sometimes think I don't know how much the ARUP+ programme is costing, and I don't know why BEIS need it. It's not detrimental, but it is just like getting the same result from a bigger resource" (WP Contractor)*

Conversely, others felt this facilitated more efficient programme management overall, as it was helpful having Arup+ as an intermediary to help coordinate requests to DESNZ for information needed by the work package contractors. DESNZ representatives also highlighted that having Arup+ co-managing Hy4Heat helped to source input from a diverse range of experts to advise on technical matters in throughout the programme. Arup+ is a consortium of organisations with expertise in different areas and able to provide not only logistical support but also technical advice.

Some non-Arup consortium partners of Arup+ noted they were not invited to Programme Board meetings, meaning they had less sight of monitoring and reporting processes and less direct engagement in feeding in technical advice. One respondent suggested that an alternative model, which was closer to traditional standard practice in their industry, would be for technical advisors to have two relationships: a direct advisory role to their client (DESNZ in the case for Hy4Heat), and a separate sub-contractor role to Arup who could instruct other consortium parties for supplementary tasks on behalf of DESNZ (the client). At present, all Arup+ consortium members generally communicate through Arup project managers.

> *"I would do the governance of the project differently in future. And I'd have two direct relationships between BEIS… the technical advisor or advisors, and the project management company. And that's not to say a project management company can't still be responsible for and can't still instruct on behalf of their client, [to other WP contractors] but it means that any technical advice that is given…is given directly and from a technical perspective, rather than filtered through any other managerial or commercial perspective." (WP Contractor)*

One contractor interviewed questioned whether the budget allocated for the WP1 programme management role was a cost-effective use of resource. Suggesting that if DESNZ managed contractors directly, this portion of the Hy4Heat could, in principle, have been reallocated to other tasks such as further development of commercial appliances. However, other stakeholders noted that given the input of Arup+ on both programme management and

[28] BEIS was superseded by DESNZ in February 2023.

providing consultants with technical expertise (including leading the Quantitative Risk Assessment), overall, the WP1 role provided good value for money.

> *Some of the suppliers moaned about it [the amount of budget allocated to WP1]. But I don't know what should have been done differently, in hindsight. You know, we use similar type of people in our own R&D projects. There are some expensive consultants that get involved, but they did a good job, so I think they got the right team (GDNO representative)*

In November 2021, Hy4Heat won the Association of Project Management's Programme of the Year Award 2021 having been judged to have "demonstrated the most effective use of programme management techniques, achieved the greatest results, and provided evidence of innovation and lessons learned for the profession" from the entrants. In addition, Arup was also shortlisted for an MCA (Management Consultancies Association) Award for their role and managing Hy4Heat delivery.[29]

Effectiveness of the procurement structures and processes

Engaging with applicants and contractors

Hy4Heat has undertaken extensive work to engage with the supplier market and potential work package applicants. In part, this has been facilitated through collaborating with relevant trade bodies to drive programme awareness amongst its members. Based on the feedback received at pre-tender supplier engagement events, DESNZ acted upon suggestions given and changed the tender requirements where appropriate. The Hy4Heat website also provided an effective way of engaging with prospective applicants, providing sufficient information about the programme and the tender requirements.

In addition to pre-tender supplier engagement, Hy4Heat also ran wider awareness raising events. This included general stakeholder engagement events (inviting wider manufacturers, trade bodies, academics etc) to showcase the programme achievements and to share information on its future direction. At the events, DESNZ and Arup+ staff presented overviews of the aims of work packages and facilitated question and answer sessions with prospective bidders of future work packages.

Several attendees at supplier engagement events that were interviewed as part of the evaluation spoke of feeling listened to, and that communication from DESNZ had been very effective. In particular, many agreed that DESNZ and Arup+ had clearly and effectively articulated the aims and objectives of the Hy4Heat programme and the specific work packages. Although some attendees interviewed said they felt slightly unclear on the precise role of Arup+ in decision making.

Developing tender documents and scope of work

A review of each work package's tender documents by the study team suggests that they were clearly written, while also providing detailed information on the policy and technology context underpinning the programme, the programme's aims and objectives, the technical requirements of the tender, and the procurement procedures. Interviewed applicants almost

[29]https://www.mca.org.uk/consulting-case-studies/arup-with-department-for-business-energy-and-industrial-strategy-beis

universally agreed with this assessment, saying that the tender documents were clear, well written, and easy to understand.

Many of the interviewed contractors and unsuccessful applicants alike said that their work package's scope of work, as detailed in the tender documents, was fair and appropriate. Overall, contractors felt that their respective work packages covered all the necessary technical elements, with no major omissions nor any superfluous work elements.

Application, assessment and procurement process

Although only a small number of attendees at supplier engagement events who decided not to bid for work packages were interviewed, there appear to have been no consistent barriers that prevented them from bidding. Reasons for choosing not to apply included not being eligible as a public sector organisation, an inability to form a suitable consortium, and the belief that the programme would not see SMEs as credible applicants.

Interviewed applicants generally reported the application process as being relatively straightforward. As noted above, tender documents were clear, had sufficient detail, and there were opportunities for dialogue with DESNZ to clarify elements of the scope of work. Transparency has been central to the programme's application and procurement process. The Hy4Heat website has held all the tender documents published, as well as supplementary information such as additional guidance notes, notes from suppliers' events, and answers to clarifications requested by bidders. Furthermore, all the interviewed unsuccessful applicants spoke of how they received detailed feedback as to why their bids were unsuccessful.

When probed, the majority of interviewees said that they could not think of many ways of improving or streamlining the application and assessment process they experienced. By and large, applicants felt there was sufficient time to prepare the applications and did not feel the need for additional support or guidance from DESNZ.

Nevertheless, there were conflicting views amongst some contractors on the appropriateness of procuring work packages via SBRI. One contractor said that one of the main reasons they applied for the work package in the first place was because under SBRI, they were able to keep any IP developed. However, one respondent said they had real concerns about whether they would be able to retain arising IP developed through Hy4Heat. This was reported to have led one other boiler manufacturer deciding not to participate in the programme, choosing instead to develop hydrogen appliances through alternative routes instead.

Feedback gathered indicates that the programme received sufficient numbers of high-quality bids, albeit that for some work packages there was not a large pool of potential applicants that Hy4Heat could target (such as contractors with safety testing facilities for WP7).

Assessments

In terms of the assessment process, consultees raised few concerns and suggested the process generally worked well. It was felt that the submitted bids generally provided sufficient information to allow a thorough assessment of each application. Each Invitation to Tender contained the assessment criteria to be used and, according to assessors, applicants had generally paid close attention to this in their responses. Some applicants, especially unsuccessful ones, did however, allude to it taking the assessment panel longer than anticipated to reach a decision on applications.

More generally, respondents commented on the assessment panel having the right range of expertise and experience to enable an accurate assessment of each proposal. Each panel has covered a mix of; safety and technical expertise from Kiwa, delivery and project management knowledge from Arup, and value for money assessment from DESNZ. Consultees alluded to how they felt that this was an appropriate approach. It enabled the procurement exercise to appoint the bidder best placed to deliver the contract.

Procurement and contracting

Overall, successful applicants had few complaints about the processes involved in both drawing up and then signing a contract with DESNZ. The majority indicated that the contractual terms and conditions were clear. Several contractors highlighted that DESNZ were open to discussing and clarifying contractual details where appropriate. A small number of contractors did indicate a certain lack of clarity over required milestones. For example, whether certain reporting deliverables were recommended as good practice or contractually required.

Some respondents noted that there were delays in timescales of the procurement process, with the tender assessment process taking longer than indicated to complete and for contracts to be awarded. However, once contracts were awarded, WP contractors were still expected to meet the timelines of original specification, although time had already slipped before project inception. This was reported to have led to some work being condensed and highly resource intensive in order to bring timescales back on track to meet first milestones.

There were some concerns amongst the most recently appointed contractors that the original March 2021 delivery deadlines were too tight, especially in the context of Covid-19. However, consultees commented on how DESNZ was open to extending the project timescales in light of the circumstances, and for a few WPs, DESNZ has extended project completion up to December 2021.

Monitoring and work package oversight

The Hydrogen Co-ordination Group and the Advisory Panel members interviewed reported they received sufficient information on the progress of each WP. One GDNO stated that the groups have been given plenty of opportunities to provide inputs to the running and management of the programme, both through official meetings and bilateral conversations. There is a perception amongst members of both groups that Hy4Heat contractors have taken their views into account. They felt that Arup+ has been responsive and quick to action the advice, making changes or additions to various work strands. For example, decisions to commission WP10's work on hydrogen meters arose after the programme had already commenced, partly as a result of challenge from the Hydrogen Co-ordination Group and the Advisory Panel which highlighted smart meters as a gap.

> *"The Advisory Panel meetings are very open and very receptive so if the Panel is suggesting something, Arup minute it, take it away and bring it back as an action next time. It's [a] continuous loop and things don't get forgotten in that environment" (Advisory Panel member)*

However, there was some suggestion the Hy4Heat Programme Board was not always quick to action ideas from the Hydrogen Co-ordination Group and Advisory Panel as members expect. For example, both the Hydrogen Co-ordination Group and the Advisory Panel recommended the development of a cross-cutting WP developing a hydrogen competence framework for engineers installing appliances for the community trial. Although this was subsequently

commissioned, one GDNO representative stated some frustration over the initial reticence of the Hy4Heat Programme Board in agreeing to proceed with this, and that it could perhaps have commenced at an earlier stage. DESNZ officials explained that one reason for this delay was that they required WP2 work strands on developing industry standards to have progressed sufficiently before commissioning work on the competence framework.

Work Package oversight

Arup+ project managers commented that they had enough information and interactions with each of the WPs to monitor progress. They commented on having sufficient information on delivery against milestones and delivery dates (including any COVID support requests) and notes from meetings between the different WP managers and Arup+ technical leads.

WP contractors reported the milestone deadlines as generally being tight, but necessary to move the overall programme forward, given interlinkages between WPs.

It is also clear that for some of the work packages, the Arup+ consortium has maintained close contact with WP contractors. One contractor spoke of Arup+ being very approachable and committed to maintaining a good relationship with them, while others spoke of using the consortium as a source of technical advice. Several contractors also spoke of them having good and regular communication with Arup+. Having monthly progress reports and ad hoc meetings in between seemed to work well and provided a good way of monitoring progress against milestones.

Some WP contractors suggested specific areas for improvement around agreeing the precise monitoring, verification and reporting requirements. For example, on WP10, contractors reported the requirements for site visits and verification were not clearly specified at the project inception stage. Some contractors mentioned that the monitoring and reporting processes could have been more efficient if the frequency to present the monitoring and management reports would have been lower as well as the information required less repetitive. One respondent stated that more guidance from DESNZ and Arup+ on the content of the reports and the formats would have been very useful to save some time during the reporting stages.

> *“Some parts of the process could have been managed differently to make the whole process more agile. Likewise, there were internal progress and management reports and sheets that we needed to fill quite often which wasn’t particularly useful”. (WP6 Contractor)*

Interaction between the different work packages

A core part of Arup+’s remit is to help facilitate knowledge exchange and interactions between the different work packages, in part to make the development of new solutions more effective and efficient, but also to ensure that the outputs from each work package are compatible with one another (e.g., to ensure that appliances meet the same standards and safety requirements). Respondents reported several instances where contractors from different work packages had collaborated with each other:

- The development of the PAS4444 standard for WP3 included the creation of a steering group whose members included other contractors within Hy4Heat, particularly WP2 (namely IGEM), and WP4.
- IGEM and EUS collaborated on the development of skills and competency framework. The collaboration between these two organisations will continue in the future as they

have secured additional funding from DESNZ to conduct further research and fill in the gaps that emerged as part of their work in Hy4heat.

- Interaction of BAXI (WP2) with WP3 (namely EUS) and WP7 collaborating in the development of the standards framework and safety components but not in a contractual manner.
- Visits by Continental (WP4b) to Hy4Heat boiler manufacturers.
- Close working relationship between Element Energy (WP6) and those involved in WP5, instigated through Hy4Heat.
- Arup+ helped broker relationships between Steer Energy (WP7) and relevant manufacturers on safety issues.
- Stakeholder engagement events organised by DESNZ and Arup+ which helped bring different work package contractors together.

While there has been some interaction between different work packages, it appears that a number of these have been more informal in nature, with the exception of input to collaborative strands such as developing standards and certification. Where collaborations and interactions have taken place between different work packages, some have occurred organically, without Arup+ playing a formal intermediary role.

While some contractors have engaged with various other WP leads, other contractors have not substantively interacted with any others. Respondents provided a variety of reasons for this. In some cases, contractors said that they could not see any need for, or benefits from, collaboration with other work packages. Particularly where this would have meant sharing information with potential competitors. In others, there was a clear intention and desire to meet with other contractors, but Covid-19 restrictions have prevented this. Also, some contractors stated that they were expecting to receive both more information about other WPs performance and more frequent updates of the overall progress of the programme. It was felt that Arup+ could have had a more proactive role as an intermediary between WPs.

> *"There was not information coming to us from any of the work packages and events related to Hy4Heat. I was expecting to see a little bit more engagement with the work packages, but I've never heard about what other WP were doing". (WP contractor)*

Wider stakeholder engagement and dissemination

The programme has undertaken a variety of publicity and public engagement activities, such as communication through the website and newsletters, as well as presentations (including at COP24 in Katowice, COP25 in Madrid and COP26 in Glasgow) and publication of annual progress reports. Hy4Heat has developed a clear brand with a transparent website which showcases progress made by each work package and by the programme as a whole. By having a combination of reports and technical guidance documents, the website may also be useful as guidance to non-Hy4Heat participants interested in developing hydrogen products.

A stakeholder engagement event held in March 2020 was well attended (over 200 participants) by a wide variety of different organisation types, including: appliance manufacturers and retailers, academics, energy industry consultants, trade bodies and associations, gas distribution network operators, exhibition agencies and the media. Compared to the first engagement event held in 2018, the number of attendees had doubled, suggesting that

Hy4Heat is now gaining greater attention within the gas engineering and technology community.

There is new evidence that the programme is gaining traction especially in the international arena. Some consultees mentioned that in the last months they have been contacted from governmental departments (UK and abroad) and international organisations which are interested in the programme's results and would like to integrate some findings into their work. For example, WP 3 contractors who developed the purity and colorant standards have received several enquiries from overseas especially from companies in Australia, America and Japan who are interested in developing their own ISO standards. Some consultees indicated that a few of their clients have also shown interest in their Hy4Heat outcomes and in one case one of the respondents mentioned that the company has even started negotiations with potential investors.

Wider learning from the evaluation for DESNZ

Over the course of the evaluation, we have collected evidence that provides more general learning for DESNZ to inform the design of future innovation programmes. We briefly set out the evaluation team's views on two wider potential learning points below.

Communications and information availability

The Hy4Heat programme has a bespoke website[30] which provides information on what the programme's aim and objectives are, what work is taking place in the individual Work Packages, progress made and project completion reports. The website also provides historical documents, such as the Invitations to Tender for the different work packages, slides from previous stakeholder engagement events and details of industry conferences where Hy4Heat work has been presented. The website provides more information, in one centralised source, than is commonly available for other DESNZ Energy Innovation Portfolio (EIP) programmes. Information on other EIP programmes is primarily provided via the gov.uk website[31]. This typically provides a relatively brief overview of; the aims of each programme, competition guidance documents aimed at suppliers who may have interest in tendering and brief summaries of the aims of projects funded.

Some industry stakeholders commented on the usefulness of the Hy4Heat website as a centralised source of information to gain an understanding of progress on Work Packages, how they interlink to meet overall objectives and publications of findings to date. A quarterly newsletter on progress is also distributed to a wide circulation list of industry stakeholders. While this level of bespoke online communications is over and above what is typically provided for other EIP programmes, it appears to have been appropriate given one of Hy4Heat's aims was to stimulate industry to invest in wider R&D. Developing individual programme websites may not be appropriate or necessary for all EIP or NZIP programmes, but may be considered useful for programmes which have a similar emphasis on working collaboratively with industry to meet longer term goals on advancing technology development and deployment.

[30] https://www.hy4heat.info
[31] https://www.gov.uk/guidance/energy-innovation#beis-energy-innovation-programme-funding-closed

Implications of refining programme aims

Some respondents interviewed commented that the original aims of Hy4Heat (summarised in quote below) were broad ranging and created some uncertainty on the scope of work.

> *Our mission is to establish if it is technically possible, safe and convenient to replace natural gas (methane) with hydrogen in residential and commercial buildings and gas appliances. This will enable the government to determine whether to proceed to community trial.*

As discussed in previous Sections of this report, Hy4Heat has developed a limited range of commercial appliance prototypes and the scope of safety work in buildings was limited to certain types of residential buildings, rather than all types of residential and commercial buildings. The rationale for this prioritisation was that it maximises use of available budget to provide sufficient evidence to enable development of the first neighbourhood trial (focusing on types of residential properties within this scope). Some respondents noted that, whilst there is good rationale for this prioritisation, it requires careful management of expectations and consideration of what evidence gaps will need to be addressed in future. For example, to inform progression of future community trials that may cover wider building types. A DESNZ official interviewed suggested that, when prioritisation in the focus of aims occurred, the implications for remaining evidence gaps could have been more clearly documented and communicated to wider policy teams. A learning point is that clear communication of what evidence a programme will and will not provide, would provide timely information to inform decisions on what future R&D needs to be commissioned and when strategic decisions on decarbonisation pathways can be made.

Conclusions

This evaluation of the Hy4Heat programme had four main aims, in summary:

1. Identify the overall programme benefits and impacts
2. Assess the extent to which the programme has achieved its objectives; including whether the evidence needs of policy teams have been met to inform decisions on progressing with a community trial
3. Assess the cost effectiveness of the programme by understanding the issues associated with value for money and comparing Hy4Heat's cost effectiveness to other similar innovation programmes
4. Assess the effectiveness and efficiency of programme implementation, including the contracted project management, procurement structures, and internal governance structures.

The main conclusions that can be drawn the evaluation are summarised for each of these aims in turn below.

Overall programme benefits and impacts

Hy4Heat has achieved, or is on track to achieve, all of the key outcomes and impacts that were mapped out in the programme Theory of Change. It also contributing towards wider benefits such as stimulating external industry to invest in R&D that will support wider hydrogen conversion goals. Notable achievements include the development of a range of hydrogen heating and cooking appliance prototypes, plus ancillary components, to demonstration stage from a starting point of low TRLs (1-2).

Variable progress has been made on TRL advancement between Hy4Heat WPs. WP4 (domestic appliances) has advanced furthest; reaching live public demonstration of the functional performance of a range of heating and cooking appliances. Prototype commercial appliances have also been developed although they have not yet reached the same level of testing, verification and demonstration stages as WP4 appliances. Decisions to prioritise advancement of domestic appliances were based on pragmatic consideration of what evidence is needed in 2021 to inform design of the first community trial, focusing on residential buildings.

Some stakeholders felt that Hy4Heat's most important achievement has been receiving validation from the Health and Safety Executive (HSE) for the safety assessment developed as part of WP7. The risk assessment indicates that usage of 100% hydrogen can be as safe as natural gas when used for heating and cooking in detached, semi-detached, and terraced houses of standard construction. This outcome was key to enabling the development of the first community trial, led by GDNOs, to progress towards implementation. It was also reported to have stimulated interest from the leads of wider hydrogen innovation programmes, both in the UK and internationally.

The safety assessment outlines a range of recommendations to further strengthen evidence on the safety of using hydrogen for heating. These include; applying the safety assessment to a cover a broader range of building types and to conduct experimental testing on the impact of

hydrogen explosions. Nevertheless, these gaps were not considered within scope of the Hy4Heat WPs. The safety assessment underwent HSE assurance and was found to provide an appropriate basis for designing and informing the risk assessment for a trial.

Providing evidence to inform policy decisions on progression to a community trial

The core aim of Hy4Heat was to establish if it is technically possible, safe and convenient to replace natural gas (methane) with hydrogen in residential and commercial buildings and gas appliances. This evidence was needed to enable the government to determine whether to proceed to community trial. At the time of programme launch in 2017, no decision had been taken on whether to support a community trial.

In November 2020, publication of the government's The Ten Point Plan provided confirmation of government's commitment to progress with trials on the use of hydrogen appliances in real domestic settings. The target milestones included beginning hydrogen heating trials in a local neighbourhood by 2023. Additional targets include that by 2025, government will support industry to begin a large village hydrogen heating trial and set out plans for a possible pilot hydrogen town before the end of the decade.

Evidence gathered strongly suggests Hy4Heat played a meaningful role in contributing towards decisions to progress with community trials. As noted above, without approval of the safety assessment downstream of the meter conducted under Hy4Heat, GDNOs would not be able to confirm implementation of the H100 trial in Fife. Hy4Heat was also key to the development of appliances and ancillary components downstream of the emergency control valve, which are outside the remit of GDNOs licensing obligations.

Value for Money assessment

Although primarily drawing upon a qualitative assessment of overall value for money, there is reasonable evidence to suggest that the Hy4Heat programme has been delivered in a cost-effective manner. The key evidence to support this conclusion includes:

- Technological progress being made at an appropriate cost - at a lower average cost per TRL increase than the wider DESNZ energy innovation programmes
- The programme reducing potential duplication of activities, and timescales for completion, compared to if they had been delivered by the private sector in the absence of the programme
- Coordination and engagement with relevant organisations meant challenges could be overcome rapidly to allow key outputs and outcomes to be achieved
- The value of grants being made through the programme to support technical progress being broadly comparable to the wider Energy Innovation Portfolio (EIP)
- Qualitative interview evidence suggests Hy4Heat has stimulated increase in R&D relating to Hy4Heat. This is supported published commitments on websites of GDNOs and wider appliance manufacturers.

Effectiveness of programme design and management

The arrangements to work collaboratively with industry stakeholders that were put in place as part of programme design were highlighted as being beneficial. This enabled GDNOs to feed in views to Hy4Heat programme management on which areas the programme should prioritise

and, vice versa, for senior managers of Hy4Heat to identify any gaps in the development of technologies or components which may be within scope for GDNOs to cover in their R&D. This enabled government, GDNOs and trade body representatives to take a holistic view of the hydrogen supply chain from transmission through the networks to end usage of appliances within homes, identify gaps and agree 'who does what' to address them.

Some respondents felt that having a programme management contractor in place (Arup+) facilitated more efficient programme management. Given the breadth of coverage of Hy4Heat's ten WPs, it was effective to have a programme management contractor to monitor progress, identify and assess risks and to coordinate requests to DESNZ for information. Arup+ also acted as a reliable resource for securing input from experts to advise on technical matters throughout the programme, particularly for leading the safety assessment. For other WP contractors more accustomed to direct engagement with DESNZ, some felt the programme management contractor role created an extra layer of bureaucracy and prevented direct access to DESNZ officials.

Finally, it should be noted that many of Hy4Heat's core WPs were being delivered throughout the Covid-19 pandemic. Although this caused delays to project completion dates, the fact that Hy4Heat has, within this context, still been able to demonstrate that it is technically possible, safe and convenient to replace natural gas (methane) with hydrogen across a wide range of appliances can be concluded as being a considerable success. Further work will be needed to understand the cost and feasibility of proposed safety measures, as well as to determine whether determine whether hydrogen can safely be used in distribution networks and wider types of building that were outside the scope of Hy4Heat.

Annexes

The following Annexes have been provided as separate documents:

Annex	Title
A	Evaluation Plan and Methods
B	Case Studies: International hydrogen for heating programmes
C	Hydrogen investment trends and patents
D	Process Tracing results
E	Excel Framework of Process Tracing tests

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