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Greenhouse Gas Inventory Improvement Programme - Project 4: Hydrogen

Final Report

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Glossary

AD	Activity data
AFLEET Tool	Alternative Fuel Life-Cycle Environmental and Economic Transportation
ANRP	Automatic number-plate recognition
AQP	Air Quality Pollutant
AQPI	Air Quality Pollution Inventory
ARENA	Australian Renewable Energy Agency
ATR	Autothermal reforming
BAT	Best available techniques
BRT	Below reporting threshold
CC	Carbon Capture
CCS	Carbon Capture and Storage
CCUS	Carbon Capture, Usage and Storage
CEFC	Clean Energy Finance Corporation
CH_4	Methane
CO	Carbon monoxide
CO_2	Carbon dioxide
COMAH	Control of major accident hazards
COSH-AIR	Community scenarios of hydrogen energy and impacts on air pollution
CRF	Common Reporting Format
CSIRO	The Commonwealth Scientific and Industrial Research Organisation
DA	Devolved Administration
Defra	Department for Environment, Food and Rural Affairs
DESNZ	Department for Energy Security and Net Zero

DfT	Department for Transport
DN	Distribution Networks
DUKES	Digest of UK Energy Statistics
EA	Environment Agency
ECUK	Energy Consumption in the United Kingdom
EEMS	Environmental Emissions Monitoring System
EFs	Emission Factors
EFDB	EFs Database
EIGA	European Industrial Gases Association
EMEP/EEA	European Monitoring and Evaluation Program
EPR	Environmental Permitting Regulations
ETS	Emissions Trading Scheme
F-gases	Fluorinated gases
FSO	Future systems operator
GCVs	Gross calorific values
GDN	Gas distribution networks
GHG	Greenhouse gas
GREET	Greenhouse Gases, Regulated Emissions, and Energy Use in Technologies model
GW	Gigawatt
H_2	Hydrogen
HAR	Hydrogen Allocation Round
HESC	Hydrogen energy supply chain
HFCs	Hydrofluorocarbons

HMRC	HM Revenue & Customs
IEA	International Energy Agency
IED	Industrial Emissions Directive
IPCC	Intergovernmental Panel on Climate Change
IPHE	International Partnership for Hydrogen and Fuel Cells in the Economy
IPPU	Industrial Processes and Product Use
JRC	Joint Research Commission
KHI	Kawasaki Heavy Industries
LCA	Life cycle analysis
LCP	Large combustion plants
LDZ	Local Distribution Zone
LOHC	Liquid organic hydrogen carriers
MCPD	Medium combustion plant
MRV	Measurement, Reporting, and Verification
N_2O	Nitrous oxide
NAEI	National Atmospheric Emissions Inventory
NCs	National Communications
NCVs	Net Calorific Values
NETL	National Energy Technology Laboratory
NF_3	Nitrogen trifluoride
NH_3	Ammonia
NIEA	Northern Ireland Environment Agency
NIRs	National Inventory Reports
NMVOCs	Non-methane volatile organic compounds

NO_2	Nitrogen dioxide
NOx	Nitrogen oxides
NC	8th National Communication on Climate Change
NRMM	Non road mobile machinery
NRW	Natural Resources Wales
NSTA	North Sea Transition Authority
NTS	National Transmission System
OPRED	Offshore Petroleum Regulator for Environment and Decommissioning
PAHs	Polycyclic aromatic hydrocarbons
PFCs	Perfluorocarbons
PI	Pollution Inventory
$PM_{2.5/10}$	Fine particulate matter
PRTR	Pollutant Release and Transfer Register
QA	Quality assurance
RIDB	Regulators' Inventory Database
R&D	Research and development
SAF	Sustainable Aviation Fuel
SDE++	Sustainable energy production subsidy scheme
SEPA	Scottish Environmental Protection Agency
SF_6	Sulphur hexafluoride
SGHP	Shell Gasification and Hydrogen Production
SLM	Shrinkage and leakage model
SMR	Steam methane reforming
SO_2	Sulphur dioxide

SO_x	Sulphur oxides
TFI	The Task Force on National Greenhouse Gas Inventories
UK ETS	United Kingdom Emissions Trading Scheme
UK GHGI	United Kingdom Greenhouse Gas Inventory
UK IIR	United Kingdom Informative Inventory Report
UKRI	United Kingdom Research and Innovation
UNFCCC	United Nations Framework Convention on Climate Change
UNECE	United Nations Economic Commission for Europe
US	United States
US EPA	United States Environment Protection Agency

Executive summary

Scope and objectives of hydrogen GHG inventory improvement project

This hydrogen project, as part of the Greenhouse Gas Inventory Improvement Programme, has been led by Mott MacDonald Limited with support from Ricardo PLC and National Physical Laboratory (NPL) on behalf of DESNZ. The project objective was to develop an understanding of the current and expected future production and use of hydrogen, and identify data needs to develop the basis for the UK NAEI to accurately estimate direct GHG emissions and AQP from the hydrogen value chain.

Project phases

This project reviewed the hydrogen value chain and mapped out the GHG and AQP emissions arising from each value chain stage, including hydrogen production, transportation, storage, and end use. This project was delivered in two phases:

- Phase 1 comprised the value chain mapping exercise and concluded in July 2023; the outcome of this phase was a prioritised list of topic areas for exploration in Phase 2.
- Phase 2, the subject of this report, focussed on reviewing data and methodologies for assessment of emissions within the NAEI for the priority areas identified in Phase 1.

Priority areas identified in Phase 1

Through a prioritisation exercise the project identified key priority areas for development of the NAEI inventory data and reporting methods. The priority areas identified in Phase 1, and agreed with DESNZ, are as follows:

- Hydrogen fugitive emissions – Fugitive emissions of hydrogen across the hydrogen value chain (including emissions arising from production, storage, transport, transformation, and end use).
- Hydrogen use in combustion and fuel cells – Atmospheric pollutant (NOx only) and GHG emissions (N_2O) from hydrogen consumption, including all use cases outlined in the prioritisation exercise (combustion or fuel cells in domestic, industrial, transport, and power generation).
- Grey and blue hydrogen production – GHG inventory methodology update to account for carbon capture.
- Ammonia as a hydrogen carrier – Ammonia fugitive emissions from ammonia production, transport, storage, and reconversion to hydrogen.

Phase 2 data review and methodologies for priority areas

In Phase 2, the project team reviewed each priority area and set out the data and inventory reporting methods needed to report GHG and atmospheric pollutant emissions in the NAEI. To develop these methods, the team conducted an extensive literature review and engaged with stakeholders across government, regulatory bodies, industry, and academia.

The stakeholder engagement and literature review found that the policy and regulatory landscape for hydrogen in the UK is still under development, with some areas more developed than others, meaning that for certain emission sources there remains high uncertainty on how these will be regulated and what monitoring and reporting requirements these will be subject to. However, there are differences between priority areas; and across value chain stages, with some areas already well covered by existing regulation and MRV mechanisms (e.g. large industrial installations reporting under IED/EPR and those covered by UK ETS or EU ETS).

With regards to activity data (AD) and emission factors (EFs), although there is a significant level of research underway in many of the priority areas and emission sources, at the time of this report there is generally a lack of measured or good quality data estimates across all priority areas. However, there are few reports and research projects that have produced, or are in the process of producing, outcomes that could be of use for initial reporting approaches, for example the hydrogen fugitive emission rates published by Frazer-Nash (2022) and hydrogen combustion NOx EFs from the EMEP/EEA 2023 Guidebook.

Hydrogen fugitive emissions

For hydrogen fugitive emissions, the availability of data is considered likely to vary across the value chain, with challenges for more diffuse sources, for example leakage in smaller combustion units in domestic and commercial settings and for transport by means other than pipeline. While there are some published estimates of fugitive emission rates, these are subject to assumptions and high uncertainty ranges. There is considerable research underway to improve the ability to measure hydrogen leakage, which could theoretically be used to improve leakage rates estimates across the value chain; however, this would require additional effort to implement these techniques to improve estimates for those areas unlikely to be incentivised by existing regulation, for example transport by means other than pipeline, and hydrogen use in domestic and commercial settings.

Hydrogen use in combustion and fuel cells

Atmospheric pollutant (NOx) emissions from combustion of hydrogen are considered likely to be well-covered by existing regulation under the IED for combustion in large installations (e.g. power, industry). However, there is a significant regulatory reporting gap when it comes to smaller combustion units in domestic and commercial settings. Work underway by the COSH-AIR project is likely to improve understanding of the magnitude of this potential impact, which could inform requirements for future research.

Grey and blue hydrogen production

GHG emissions (non-H_2) from new, standalone grey and blue hydrogen production are considered likely to be well-covered by existing regulation and reporting practices via the ETS. The NAEI is likely to be able to access verified data for these emissions, and therefore the availability of relevant EFs is likely to be less of a concern (as these could be derived from ETS data). There will be a need for AD and other metrics (hydrogen production figures) to also be available through ETS reporting or DESNZ Energy Statistics commodity balance.

Ammonia as a hydrogen carrier

Reporting of fugitive emissions of ammonia for use as a hydrogen carrier is considered to be underdeveloped and, while acknowledged by many stakeholders as a potential issue, its significance is not well understood.

Development of inventory data and methods

The NAEI does not currently include any hydrogen-specific emission source methods, however there are analogous emissions sources methods (e.g. relating to the energy system reporting and consumption of other gaseous fuels) that are useful to identify the likely data and modelling requirements to be developed for the hydrogen value chain.

The project found that for many new hydrogen economy source categories, new standalone inventory models will need to be developed, whilst for other source categories it may be practicable (and preferable) to integrate the new method requirements within existing NAEI models. This was outlined in the methods proposed for each priority area.

The data and inventory methods proposed for each priority area were developed considering the varying readiness levels of data reporting systems and datasets. Where it is considered that there could be value in implementing an interim approach to improve the completeness of the inventory (where such methods would be unlikely to be immediately superseded), an **initial approach** is proposed to include the source in the inventory in the short term. This is followed by an **improved approach** that would take advantage of data from upcoming research projects and/or opportunities to utilise measured or and/or installation-level data when available in the future.

‘Ideal’ data reporting system

The project concluded that whilst individual source category methods are based on a range of primary and secondary data reliant on different reporting mechanisms, there are common reporting systems and datasets that would enable regular, high quality data supply to the NAEI. These systems are considered to be a ‘reasonable ideal’ for the UK to aim for in the medium to long term, based on existing legislation, regulation and reporting practices. These systems and datasets include:

- A detailed and highly resolved hydrogen commodity table prepared by DESNZ Energy Statistics.
- Installation-specific data from the ETS for hydrogen production emissions, with measurements for carbon capture volumes (for blue hydrogen production).
- Installation-specific data for hydrogen consumption AD at large installations (this is not covered by the UK ETS so other reporting mechanisms will need to be established).
- Measured NOx releases for all sites under the IED, or values that have been calculated using consistent methods, assumptions and EF.
- Measured ammonia releases for all sites under the IED and/or PRTR, or values that have been calculated using consistent methods, assumptions and EF.
- Measurement of hydrogen fugitive emissions, including leakage, from new hydrogen pipelines and from blending in the existing gas transmission and distribution system, or model that has been calibrated with measurements.
- Well developed, country specific hydrogen fugitive EFs across value chain stages other than pipeline transport.
- Well developed, country specific EFs for combustion of hydrogen NOx emissions in all applications across the value chain, particularly for diffuse transportation and consumption activities.
- Well developed, country specific EFs for ammonia fugitive emissions across value chain stages, particularly for diffuse transportation, storage, and consumption activities.

The establishment of this ‘ideal’ reporting system and datasets would require:

- The majority of the hydrogen value chain to be covered by regulation with clear boundaries and guidance, with no significant gaps between regulatory bodies.
- Reporting requirements under applicable regulation to be of sufficient granularity, based on measurement where possible or well-developed calculation methods, for AD and EFs.
- Acknowledgement across the value chain of the potential significance of hydrogen fugitive emissions, with measurement and reporting requirements in place.

Key recommendations for DESNZ

Based on the outcomes from this report and the gaps identified to enable an ideal dataset for hydrogen value chain emissions reporting in the NAEI, the project recommends a set of actions to be led by DESNZ in the short to medium term:

1. DESNZ to ensure that collaboration between the NAEI inventory agency and the DESNZ Energy Statistics team is maintained as the hydrogen commodity balance tables and their associated data supply mechanisms (e.g. industry and fuel supplier surveys, annual operator returns to DESNZ) are developed over the coming years. As the hydrogen economy develops, the precise requirements of the national inventory will continue to evolve and become clearer. There is likely a high level of granularity required in the AD that are generated in order to populate a national energy balance. The DESNZ energy statistics team has yet to develop a hydrogen commodity balance data gathering and reporting system (a draft hydrogen commodity balance, provided by DESNZ Energy Statistics, is available in Annex A). The study team notes that key features that are likely needed for the purposes of reporting the national inventory will include:
    a. A commodity balance that presents data at a similar level of resolution to the current natural gas commodity balance i.e. including reported annual consumption at a level of resolution that includes per transport mode, details of both energy industry consumption and use in fuel transformation.
    b. Resolution of annual hydrogen production data per technology and per feedstock.
    c. Information on transfers of hydrogen into / out of other commodity balance, for example where there may be transfers of hydrogen into gas blends/networks and where hydrogen is used within the production of ammonia or other hydrogen carriers, e.g. methanol.
2. DESNZ to work with government policy teams and regulators to ensure a comprehensive regulatory framework for hydrogen is implemented. Regulatory mandates should be implemented for operators to report to industry (Ofgem, NSTA) and environmental regulators (EA, SEPA, NRW, NIEA) on a regular basis. Likewise, industry operators should be mandated to provide data to Statistical agencies as required (e.g. through surveys).
3. DESNZ to work with UK ETS team, Hydrogen Regulatory Forum and industrial regulators, to ensure that requirements are set out for reporting of hydrogen AD, hydrogen fugitive emissions, GHGs and air quality pollutants through environmental and/or industrial regulation. As the regulatory framework is developed, and as a means to identify gaps, a map of institutional reporting requirements across the value chain could be developed, to enable collaboration and coordination of efforts to remove any gaps.
4. DESNZ and environmental regulators to work closely with industrial clusters to influence and track how they plan and track "first of a kind" projects and use these projects to test proposed regulations. DESNZ to promote communication between regulators and project designers, developers, and operators to ensure common understanding of data measurement and reporting challenges, with the aim to implement suitable and well resolved data reporting systems, but also pragmatic and feasible.
5. DESNZ to coordinate with UK research bodies and other government institutions to ensure research funding bodies are optimised and enhance communication and cross-collaboration between entities to deliver agreed/aligned useful outcomes. DESNZ to ensure collaboration with international inventory agencies (e.g. US EPA) to ensure research work is coordinated.
6. DESNZ to engage with research agencies to coordinate further research in obtaining a reliable well-developed set of EFs for hydrogen combustion atmospheric pollutant and GHG emissions. Our current understanding is that certain value chain emission sources and technologies, such as domestic/commercial boilers, are more developed than others. More research will be needed, and it will be important to coordinate efforts with other peers internationally like US EPA, JRC and others.

7. DESNZ to follow up on outcomes from ongoing research (e.g. by NPL and others) to obtain a reliable well-developed set of hydrogen leakage estimates from across the full hydrogen value chain. It will be important to understand the science and measurement techniques suitable across the value chain, so that the data reporting requirements through regulation can be set out accordingly (e.g. where measurement is necessary and feasible, as opposed to indirect calculation or estimation methods)
8. DESNZ to continue work with industry (e.g. gas distribution network operators) to develop a measurement-enabled model for hydrogen leakage from pipelines. Research on leakage with hydrogen blending and methods to calculate this. Engage with transport operators to develop models for non-pipeline transport and storage.
9. DESNZ to work with environmental regulators and other government agencies, like the Department for Transport, to plan and develop research in the area of ammonia fugitive emissions. This area is significantly less developed than hydrogen emissions, and it will require a common decision on the research needs and priorities in the short term, which depend on the likelihood of ammonia becoming significant as a hydrogen carrier.

1 Introduction

1.1 Scope and objectives of the GHGI hydrogen improvement project

The Hydrogen project, as part of the Greenhouse Gas Inventory Improvement Programme, has been led by Mott MacDonald Limited with support from Ricardo PLC and NPL on behalf of DESNZ. The project objective was to develop an understanding of the current and expected future production and use of hydrogen, and identify data needs to develop the basis for the UK NAEI to accurately estimate direct GHG emissions and AQP from the hydrogen value chain. The project scope included all UNFCCC-reported GHGs [1], as well as hydrogen, and main air quality pollutants such as NOx (including NO_2 emissions) from combustion processes.

The atmospheric chemistry of indirect GHGs impacts the abundance of direct GHGs, thereby indirectly leading to the absorption of infrared radiation. Gases such as carbon monoxide (CO), NOx, SO_x, and NMVOCs are indirect GHGs [2] and are already reported as precursors in UNFCCC reporting tables. Hydrogen is an indirect GHG [3] and is not currently reported in the inventory, however, recognising the likely increase in its use across the economy, the project focused on identifying emission sources and proposing methodologies to account for the impact of fugitive [i] hydrogen across the value chain.

1.2 Hydrogen value chain and areas of focus for this report

This project was delivered in two phases. Phase 1 comprised the value chain mapping exercise and concluded in July 2023; the outcome of this phase was a prioritised list of topic areas for exploration in Phase 2. Phase 2, the subject of this report, focussed on reviewing data and methodologies for assessment of emissions within the NAEI for the priority areas identified in Phase 1.

1.3 Value chain mapping (Phase 1)

A prioritisation exercise was completed to identify the emission sources of the currently known stages and processes associated with the hydrogen value chain, from production through to end use, including hydrogen derivatives. As a result of this exercise, and following a review and discussion with DESNZ, the following areas were identified as a priority for methodology review, update, and/or development:

- Fugitive emissions of hydrogen across the hydrogen value chain (including emissions arising from production, storage, transport, transformation, and end use).
- Atmospheric pollutant (NO_x only) and GHG emissions (N_2O) from hydrogen consumption, including all use cases outlined in the prioritisation exercise (combustion or fuel cells in domestic, industrial, transport, and power generation).
- Grey and blue hydrogen production methodology update to account for carbon capture [ii].
- Ammonia as a hydrogen carrier – NH_3 fugitive emissions from ammonia production, transport, storage and reconversion to hydrogen.

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[i] This includes the intentional or unintentional release of greenhouse gases, including venting, flaring and leaks, as per the 2006 IPCC Guidelines for National Greenhouse Gas Inventories Volume 2: Energy, Chapter 4: Fugitive Emissions. In this document, we will use the term 'fugitive' hydrogen emissions when referring to such intentional or unintentional release of hydrogen, and leakage when specifically referring to unintentional release from leakage.

[ii] The scope for this review is GHGs, not precursors. While it is acknowledged that there may be a small amount of CO from the production process, this is not considered further in this project as it was not identified as a priority area.

1.4 Objectives of the methodology review (Phase 2)

In Phase 2, the project team conducted a data and methodology review within the priority areas, with the overall objectives as follows:

- To review national inventories and international publications on the current and planned approaches to assessing hydrogen-related emissions.
- To review the NAEI on how data within the priority areas is currently received, processed, and reported.
- To identify data sources and propose the ideal AD and method of data capture and reporting for each priority area. The methodologies proposed to be based on the optimal selection of AD and EFs considering both the associated contribution to emissions and the difficulty in measurement.
- To outline key challenges and provide recommendations for regulators and government bodies on measures and processes required to enable hydrogen emissions reporting.

1.5 Approach for the methodology review (Phase 2)

The review required both desk-based research and stakeholder engagement with government, regulators, and other relevant experts and institutions. Desk-based research considered a range of reference documents such as international and national publications (reports, strategies, guidelines etc.), government policy documents and consultations, academic research, R&D project findings, and other countries' inventories and national communications. Stakeholders and reference documents were shortlisted and compiled based on the consultation of experts and general internet search. A bibliography is provided in Annex G.

2 International landscape review

This section of the report reviews the international landscape on emissions reporting of the hydrogen economy, aiming to identify developments in other countries regarding general policy, regulation, research and reporting that could be of use to support the information obtained in the UK. The list of literature reviewed, including international publications, national strategies and research projects are provided in Annex G.

2.1 International hydrogen landscape

The IEA Global Hydrogen Review 2023 [4] is an annual publication that examines hydrogen production and demand worldwide. While the deployment of low emission hydrogen production is still at an early stage, political momentum remains strong, with the number of announced projects and incentive programmes continuing to grow.

The IEA review noted that 41 governments, which accounts for almost 80% of global energy sector emissions, have adopted hydrogen strategies [4]. Several governments have also updated their strategies since 2022, including Germany, Japan, Belgium, and Korea.

Various incentive mechanisms have been deployed to stimulate low-emission hydrogen demand. This includes policy measures to mitigate investment risks (grants, competitive bidding etc.), innovation programmes, and certification systems. There are currently 13 governments with regulatory frameworks either in operation or under development, though the IEA review noted that specific methodologies to demonstrate their compliance are often yet to be established. The IPHE has also finalised the Methodology for Determining the GHG Emissions Associated with the Production, Conversion and Transport of Hydrogen [5], which will feed into the development of a draft International Standard proposed to be published by the end of 2024. Based on the standards and programmes reviewed, some countries like USA or Australia have developed LCA-based approaches [6], as well as guidelines and calculators for the estimation of emissions from hydrogen production [7]. The IEA review indicated the notable lack of progress in developing hydrogen leakage reporting and measurement protocols, and current information is often limited to demonstration projects.

2.2 Selected countries review

The reviewed countries are listed below:

- US
- Australia
- Netherlands
- Japan
- Germany

Their 2023 national inventory submissions [8], pollutant inventories, funded projects, and NC were reviewed to understand the current and planned approaches on reporting emissions within the hydrogen value chain. This aimed to identify the status of hydrogen reporting in their inventories, and where applicable review the AD sources, the type of EFs and their associated assumptions, as well as the methodologies currently being used by other countries.

The review process of the national inventories and NCs involved:

- Search keywords (hydrogen, H_2, fuel cell, alternative fuel) in documents.
- Review general parts of the NIRs on improvement areas and emerging trends.

- Review sections on precursor GHGs.
- Search AQPI for NOx, ammonia, and different source categories.
- Review models utilised by reporting country.

Research noted that there was limited acknowledgement of the fugitive emissions of hydrogen gas, one instance would be the US inventory, where hydrogen was reported as part of still gas but was treated as a petroleum product instead of a fugitive emission. Regarding hydrogen fuel cells and combustion, the US inventory reported vehicle miles travelled (VMT) from hydrogen fuel cell vehicles, with AD taken from vehicle sales data. The Netherlands inventory also mentioned hydrogen as a fuel type in their table of EFs for transport, with NOx and N_2O EFs for hydrogen indicated as 0 or blank [8].

Similar to the UK, many countries have demonstration projects and studies underway, with several that may possibly lead to early data on hydrogen leakage and NOx emissions. Examples include the 100% liquid ammonia combustion gas turbine project led by the IHI Corp [9] and the 100% hydrogen-fuelled gas turbine operation project announced by the KHI [10], both based in Japan. Numerous countries have also initiated or completed blending studies for their existing gas networks, such as Australia, Netherlands, and Germany. Further details per country are summarised in Annex B.

2.3 Other international research

In addition to the country reviews described above, the project reviewed other international research projects and reports relevant to the scope of work. For instance, European funded research projects such as ThyGA [11] and Flexipower [12] which have specific work streams on hydrogen emissions, as well as reports published by JRC, EIGA and other international bodies.

The review found that there is a significant amount of work underway in researching, developing, and incentivising the low carbon hydrogen economy in the international landscape. However, with regards to hydrogen value chain emissions most of the work developed so far is around LCA quantification of GHG emissions. The need to understand hydrogen fugitive emissions is starting to be recognised but any work in this area is still nascent. With regards to air quality pollutants, there are studies on the environmental impacts of the hydrogen value chain (which include NOx emissions to air) but there is little research published on quantitative data (e.g. EF from hydrogen combustion).

Overall, research showed limited information that is additional to the UK landscape, which is not unexpected given the novelty of the hydrogen economy. Therefore, the UK has an opportunity to lead on the development of these areas, and there will be a benefit in collaborating with international agencies and bodies.

3 UK data and regulatory landscape

3.1 Introduction

In addition to the international landscape review as described in Section 1.5, the project team conducted extensive stakeholder engagement within the UK, as well as literature review, to inform the development of proposed approaches for the UK NAEI. A complete list of the documents and sources reviewed is provided as Bibliography in Annex G.

The outcomes from this engagement, and the relevant projects and reports that have been reviewed, are discussed in this section.

3.2 Stakeholder engagement and literature review process

Stakeholder engagement was conducted in Autumn 2023 (concluding early December 2023). The list of stakeholders was prepared in consultation with DESNZ and included policy makers, regulators, research institutions, associations and industry representatives in the UK known to be working on hydrogen or related activities. A few international stakeholders were also proposed for engagement to understand the level of advancement and plans for hydrogen emissions reporting in other countries.

The list below includes those stakeholders who responded via email and or with whom the project team held virtual meetings.

Government bodies

- DESNZ Hydrogen Policy
- DESNZ Energy Statistics
- DESNZ Science & Innovation for Climate and Energy
- DESNZ Heat Infrastructure Transformation
- DESNZ ETS
- Defra Industrial Emissions Reporting and Pollution Inventory team
- Scottish Government

Regulators

- OPRED
- Ofgem
- EA
- NRW
- SEPA

Academia, industry & associations

- Imperial College London (COSH-AIR project team)
- University College London (COSH-AIR project team)
- Scottish Hydrogen and Fuel Cell Association
- Energy Networks Association
- Aether (EMEP/EEA Guidebook team)
- Mott MacDonald (Redcar hydrogen trial team)
- National Physical Laboratory

- HYFLEXPOWER

International

- US EPA
- IPCC Task Force on Inventories

Stakeholders were asked about ongoing work and research they may be aware of related to the emissions data collection, calculation, or measurement processes that would be relevant to a future hydrogen economy. Given that much of this research is not yet complete, the project team enquired about project timescales (where known/ public) to inform future inventory processes and when such data could realistically be used.

With the objective of understanding the planned regulatory landscape for the future hydrogen economy, government and regulators were asked about planned future policies, regulatory frameworks and reporting requirements for the hydrogen economy. The potential regulatory gaps, uncertainties, and mechanisms for data reporting were also discussed.

The engagement with industry and academia focused on ongoing and future research, to understand the challenges with regards to measurement and reporting of AD, and development of EFs for each of the priority areas.

3.3 Stakeholder engagement and literature review outcomes

The outcomes of the stakeholder engagement and literature review exercise have been categorised into the following topic areas:

- Reporting requirements for the hydrogen economy.
- Research and guidance on GHG emissions impact of the hydrogen economy (including EFs for hydrogen production).
  - Fugitive emission of hydrogen.
  - Non-hydrogen GHGs.
- Research and guidance on AQ emissions impact of the hydrogen economy.

3.3.1 Reporting requirements for the hydrogen economy

Government and regulators will have a critical role in enabling the collection of accurate AD in a future hydrogen economy. The UK Hydrogen Regulators Forum has been established to bring together regulators across the UK to promote a joined-up approach to key issues including permitting, BAT and emissions limit values.

The UK Government published the UK Hydrogen Strategy in August 2021. Since then, the UK Government has worked in developing the needed policy frameworks, with numerous ongoing consultations about the future hydrogen economy, which cover topics including but not limited to funding mechanisms, technical requirements, and environmental regulation. These consultations are focused on the production, transportation, and storage stages (rather than end use). The UK Government publishes strategy updates to the market, with the most recent one published in December 2023 [13], with a refreshed roadmap and delivery timeline out to 2035 and key announcements such as a positive strategic decision on hydrogen blending. Key policy milestones relevant to this project are summarised in the timeline presented in Figure 3.1.

As regulation is likely to be a key enabler of hydrogen data access for the NAEI, the project team developed a table (Annex C) which summarises our understanding of the hydrogen regulatory landscape across the value chain, through the lens of GHG and air quality pollutant emissions management and reporting (e.g. how these are likely to be covered by applicable regulation). The table is based on stakeholder engagement and desktop research of publicly available consultation documents and has been generated for the specific purposes of this project and context (NAEI emissions reporting requirements) – *therefore it should not be utilised out of context as it will not be a comprehensive summary of all regulation related to the hydrogen economy. Many elements of regulation are still nascent and evolving, and therefore this information is subject to change.*

The review of the regulatory landscape, through the engagement with UK Government and regulators, included an assessment of their potential ability to be providers of AD or measurements for the prioritised areas (grey/blue hydrogen production, fugitive emissions of hydrogen, hydrogen combustion/ use in fuel cells, and fugitive emissions of ammonia as a hydrogen carrier). Table 3.1 below outlines the findings of this assessment. *Please note that this table does not indicate the commitment of a regulator or body to provide such data; instead, it is the project team´s assumption based on existing remit that there would be a reasonable possibility that such data could be collected.*

Table 3.1: Consulted regulators and government bodies.

Stakeholder consulted	Potential provider of AD or measurements for:				Additional details
	GHGs from grey/blue hydrogen production	*Fugitive emissions of hydrogen*	*NOx from hydrogen combustion or fuel cells*	*Fugitive emissions of ammonia from hydrogen conversion*	
Environment regulators: Environment Agency, SEPA, NRW, NIEA[3]	Y – calculated emissions or measurements via PI	Possibly – Calculated emissions or measurements – depending on permitting/ IED requirements and available measurement techniques (likely production only)	Y – Calculated emissions or measurements (for power and industrial combustion) via PI	TBC	• Hydrogen Regulators Forum working on defining adequate regulation for hydrogen economy. • Guidance for blue hydrogen production published. Guidance for green hydrogen production forthcoming. • Looking to be proactive around minimisation of hydrogen emissions. • Working with NPL to understand monitoring options for hydrogen leakage. • Defining emissions limits for NOx for hydrogen combustion (with Defra).
Ofgem	N	Y – AD or calculated emissions – onshore pipeline transport only	N	N	• Uncertainty around detailed scope of their role until further policy clarity. • Will not regulate production of hydrogen or hydrogen storage. • Will regulate hydrogen transport via onshore pipelines.
OPRED	Unlikely – most likely will be with the DAs	Unlikely – focus on preventing major incidents only	N	N	• Environmental regulator for offshore hydrogen projects (pipelines and storage). • Offshore hydrogen production regulation is Devolved Administration (DA)-specific. • Looking at first of a kind offshore hydrogen project; their existing powers are being extended to hydrogen projects.
DESNZ – Hydrogen policy	N/A	N/A – but this seems to be a priority area they are looking at	N/A	N/A	• Next year (2024) – ongoing piece of work on policy levers to reduce fugitive emissions of hydrogen.

[3] The NIEA was not directly engaged during this project, but we anticipate that it would serve a similar function to the other DA regulators in a future hydrogen economy.

Stakeholder consulted	Potential provider of AD or measurements for:				Additional details
	GHGs from grey/blue hydrogen production	*Fugitive emissions of hydrogen*	*NOx from hydrogen combustion or fuel cells*	*Fugitive emissions of ammonia from hydrogen conversion*	
DESNZ – Energy Statistics	Y – AD, though will require changes to existing reporting. Assume this is likely to be required by IEA but not confirmed	Possibly – AD (within institutional power to collect) but unclear on data quality and whether would be required by IEA	Y – AD, though will require changes to existing reporting. Assume this is likely to be required by IEA but not confirmed, and unclear at what granularity	TBC	• IEA hydrogen commodity balance requirement by 2025 • IEA guidance on hydrogen commodity balance forthcoming. • Responsible for compiling the UK Energy Balance.
DESNZ – ETS	Y – calculated CO_2 emissions from production, measured for carbon capture volumes	Possibly – AD for production only	N	Possibly – AD if ammonia transformation within ETS	• Hydrogen production already covered by ETS.
Defra	Y – emissions via PRTR (only if over threshold – large combustion and industrial applications only)	N/A	Y – emissions via PRTR (only if over threshold – large combustion and industrial applications only)	Y – emissions via PRTR (only if over threshold – large combustion and industrial applications only)	

3.3.2 Research and guidance on GHG emissions impact of the hydrogen economy

A complete list of documents reviewed during this project is available in the Bibliography in Annex G. This section focuses on papers and projects that the project team considered most relevant to support the UK NAEI.

3.3.2.1 Fugitive emissions of hydrogen

The European Commission's JRC noted in their 2022 report 'Hydrogen emissions from a hydrogen economy and their potential global warming impact' that it is of 'paramount importance to invest in developing the ability to accurately quantify hydrogen emissions, as well as engage in more research on hydrogen leakage prevention and monitoring systems' [14].

Hydrogen emissions include fugitive emissions (including leaks) from components, process releases and slip from combustion sources. The detection and quantification of these emissions represent a number of challenges. The likely measurement scenarios are similar to those present for natural gas. For detection, scenarios include the need to detect leaks through screening of components, either by concentration detection or other techniques such as acoustic detection. While for the quantification of leaks, scenarios include approaches such as high flow-based techniques, and the quantification of site level emissions.

Hydrogen measurement challenges include the availability of measurement technologies, the behaviour of hydrogen leaks in the atmosphere and the use of blended hydrogen and natural gas. Hydrogen does not have a strong absorption in the infra-red region, and so many of the optical based techniques used for methane (natural gas) detection are not available, including remote sensing techniques and optical gas imaging. Measurement methodologies are therefore currently restricted to sensor-based approaches, though some remote sensing techniques, such as Raman spectroscopy-based approaches are in development. The behaviour for hydrogen in the atmosphere, including its more rapid dispersion and buoyancy mean that sampling approaches for leak detection may need to be modified. The use of blended hydrogen and methane means that measurement technologies that are not specific to hydrogen will need careful calibration for the blend of gas present.

Many stakeholders referenced projects and resources aimed at developing the capability to measure hydrogen leakage, which will be a key enabler for accurate emissions reporting of fugitive hydrogen, and/or improving the ability to calculate fugitive emissions of hydrogen, for example through calculated approaches or estimation of leakage rates.

As outlined in Annex D, many of the projects are ongoing and have not published final results; many are expected to be completed by the end of 2024. A summary of key outcomes from the most relevant projects, reports and guidance already completed is provided below.

- **Fugitive hydrogen emissions in a future hydrogen economy** (Frazer-Nash, March 2022) [15]: This was a DESNZ-funded research report into hydrogen fugitive emissions. The key outcomes from this report are a series of estimates for fugitive emissions rates in a future hydrogen economy under a central scenario. This scenario assumes full conversion of the National Transmission System and distribution networks to 100% hydrogen. The report covers production, transportation, storage and use, with assumptions of fugitive emissions rates at 50% and 99% emission confidence levels. While subject to assumptions and limitations, this highly relevant research project and could inform the development of an initial approach to calculating fugitive emissions of hydrogen in the NAEI (see Section 5.3.1)
- **UK Low Carbon Hydrogen Standard: Guidance on the greenhouse gas emissions and sustainability criteria (Version 2)** (UK Government, April 2023): This Standard, developed by the UK Government, is a requirement for hydrogen production projects obtaining Government funding. Compliance with this Standard requires hydrogen producers to develop a monitoring plan for hydrogen leakage, and notes that producers are expected to minimise

and report on fugitive hydrogen emissions. Approaches may include direct monitoring of hydrogen streams (for example in vent ducts) or mass balance approaches. They note that Global Warming Potential (GWP) for fugitive emissions of hydrogen are expected to be included in the emissions calculation in the future.

- **Emerging techniques for hydrogen production with carbon capture** (UK Regulators, 2023): This UK guidance was developed by Environmental regulators (EA, NRW, NIEA, and SEPA). Operators are expected to follow this guidance when applying for an environmental permit for their installation. This guidance indicates that operators should eliminate or minimise emissions of hydrogen due to its global warming potential, and that their monitoring plan should include expected pollutants including hydrogen.
- **H21 Phase 1 Technical Summary Report** (H21, May 2021): Phase 1 summary report of the H21 National Innovation Competition Project [16] outlines the differences in the leakage of hydrogen and natural gas. The study conducted tests which involved measuring leakage rates of typical gas distribution network assets at a range of pressures up to and including 7 barg with both methane and then hydrogen. The findings indicate a direct link between leakage of natural gas and hydrogen, i.e. the assets that were gas tight on methane were also gas tight on hydrogen and vice versa. The measurement of leakage from the distribution network in the study concluded volumetric flowrates of hydrogen were in line with the theoretical understanding of the leakage mechanisms under laminar and turbulent leakage regimes. This may enable conversion of leakage emissions from one system to another (e.g. natural gas to hydrogen distribution) based on the density and viscosity of the working gases and an assumption on the regime of the leakage (i.e. laminar vs turbulent flow). However, the study indicates that the ratio of the hydrogen to methane volumetric leak rates could be as high as a factor of 2 and hence more detailed understanding of the flow features and characteristics of the network, e.g. working pressure and leakage size, will be needed to improve the estimates of leakage of hydrogen via the distribution networks.

3.3.2.2 Direct GHG emissions from hydrogen production

GHG emissions other than hydrogen will occur in blue hydrogen (CC/U/S) production installations.

The projects, research and guidance identified from stakeholder engagement that are relevant to GHGs other than hydrogen (but are attributable to the hydrogen economy) are outlined below.

- **UK Low Carbon Hydrogen Standard** (UK Government 2023) & **Emerging techniques for hydrogen production with carbon capture** (EA 2023) [17]: In addition to the relevance for fugitive emissions of hydrogen mentioned above, both documents are relevant for direct GHG emissions from hydrogen production. The Emerging Techniques document states that projects should verify compliance with low carbon hydrogen standards. The UK Low Carbon Hydrogen Standard is explicitly aimed at reducing GHG emissions associated with hydrogen production and requires calculation of any GHG emissions. Reporting of GHGs is therefore likely to be required for all publicly funded hydrogen production projects.
- **Comparison of Commercial, State-of-the-Art, Fossil-Based Hydrogen Production Technologies** (US Department of Energy National Energy Technology Laboratory, 2022)[18]: This US-based study presents LCA results for key pollutants (including CO_2, NOx, SO_2, and PM) generated using modelling software, with some parameters coming from reports, vendor information performance data, and expert judgment. This study was performed on a LCA basis, and therefore, if used for Inventory purposes, care should be taken to extract only those values that represent direct emission sources that would be relevant for inventory reporting (i.e. process emissions from SMR or ATR and emissions from the CO_2 capture process) and exclude other upstream or downstream sources, e.g. consumption of grid electricity. As this study assesses state of the art technologies, it is considered to be more

representative of the types of new hydrogen production facilities that would be developed in the UK. EFs could be extracted for SMR without CCS, SMR with CCS, and ATR with CCS. A limitation of this approach is that the study assumes a natural gas composition that is typical of US circumstances, not UK.

- **GREET- H2 Model** (Argonne National Laboratory, 2022) [6]: This model is sponsored by the US Department of Energy and applies an LCA-based approach (well-to-gate) for hydrogen production. Similar to the study completed by the US Department of Energy National Energy Technology Laboratory, this model applies an LCA approach. Therefore, the same consideration applies for extracting only the relevant life cycle stages for inventory use. It should be noted that the 2022 GREET model has been updated to utilise SMR GHG emissions from the above NETL report. It does not appear that GREET includes a pathway for ATR, which is considered to be an issue for the UK as the first blue hydrogen project to receive permitting permission from the Environment Agency (Essar Oil at Stanlow Refinery) utilises ATR [19].

Evidence with regards to emissions of N_2O from hydrogen use (e.g. combustion) is very limited, in the UK only one report funded by the Scottish Government sought to understand N_2O emissions from 100% hydrogen combustion in domestic boilers [20].

3.3.3 Research and guidance on AQ emissions impact of the hydrogen economy

AQP emissions from the hydrogen economy will predominantly come from the combustion of hydrogen (e.g. gas turbines, boilers, maritime shipping and more). As of the time of writing this report, available evidence indicates that there are no AQP related emissions from hydrogen fuel cells [21].

Hydrogen combustion has the potential to generate NOx as a waste by-product (up to three times more than natural gas in gas turbines [22]), which in turn reacts rapidly in the atmosphere to form NO_2. NO_2 is a globally regulated air pollutant that is harmful to health and contributes to the formation of photochemical ozone (O_3) and $PM_{2.5}$.

Furthermore, the use of NH_3 as a hydrogen carrier, or in NOx abatement in selective catalytic reduction (SCR), may lead to fugitive emissions of NH_3, either as a result of incomplete reactions or due to inadequate infrastructure. NH_3 is harmful to human health and combines readily in the atmosphere with sulphates and nitrates to form secondary $PM_{2.5}$. The deposition of ammonia to the environment can also cause significant long-term harm to sensitive habitats.

A complete list of documents reviewed during this project is available in Annex G. A summary of key outcomes from the most relevant projects, reports and guidance considered most relevant to support the UK AQPI is provided below.

- **COSH-AIR** (Professor PaE Dodds, Dr J Woods, and Professor H Apsimon): This UKRI-funded programme includes various research strands; Professor Apsimon and team at Imperial College London are conducting a data collection exercise to build a database of EFs (primarily production and use stages). Their initial work covers use stage, focusing on hydrogen blends in domestic and commercial appliances and compiling a database of EFs for NOx and $PM_{2.5}$, with many data points coming from the THyGA project. It is anticipated that this COSH-AIR project could be a relevant source of hydrogen combustion NOx EFs for use in the NAEI, with results expected within the next year.
- **EMEP/EEA Air Pollutant Emission Inventory Guidebook: 1.A Annex Hydrogen Combustion** (Aether on behalf of the EEA, 2023): This Annex to the 2023 revision of the Guidebook outlines potential NOx EFs for hydrogen combustion in gas turbines, internal combustion engines, heavy goods vehicles, aircraft, maritime shipping, residential domestic boilers, and commercial heating boilers. In most cases these are subject to a low understanding of uncertainty and are based on a comparison to existing EFs for natural gas.

In addition, our research has indicated that a number of sources acknowledge the emissions impact of the use of ammonia as a hydrogen carrier (Princeton University [23], Ammonia Energy Association [24], Lingling Zhai et al. [25], and Matteo B. Bertagni et al. [26]), but no literature source at this time has quantified the emission rates associated with ammonia leakage and therefore further research is required. Matteo B. Bertagni et al. highlight satellites (infrared atmospheric sounding interferometer (IASI)) as being a promising tool for monitoring large ammonia leakages but acknowledge that difficulties lie with this form of monitoring due to the short atmospheric lifetime of ammonia (~hours) and that atmospheric concentrations are typically at lower levels to that detectable by satellite.

3.4 Summary of data sources reviewed and key gaps

The stakeholder engagement and literature review evidenced that the policy and regulatory landscape for hydrogen in the UK is still under development, with some areas more developed than others (see details in Annex C), meaning that for certain emission sources there remains high uncertainty on how these will be regulated and what monitoring and reporting requirements these will be subject to. Similarly, many of the research and demonstration projects reviewed are still ongoing or planned for the future years. For reference, the key milestones for relevant UK projects, policy and regulatory timeframes are set out in Figure 3.1.

Regulation is likely to be a key enabling factor for the ability of the NAEI to access quality data. Our analysis of the likelihood that certain source categories will be subject to NAEI-relevant monitoring and reporting requirements from existing or planned regulation is summarised in Table 3.2 below.

Table 3.2: Regulation Gap Analysis

	Grey/Blue hydrogen production	Green hydrogen production	Pipeline hydrogen transport	Other hydrogen transport	Combustion of hydrogen in large installations (power, industry)	Other hydrogen combustion (domestic, commercial)	Hydrogen use in transport	Ammonia as an energy carrier
GHG (non-H_2)								
NOx								
Hydrogen fugitive emissions								
Ammonia fugitive emissions								

Legend

	Likely to be well covered by existing regulation
	Discussed as an issue that will need to be addressed via regulation, but with no clear mechanism or method yet defined. Subject to moderate uncertainty
	Currently considered to be unlikely to be subject to regular monitoring and reporting requirements via regulation, or subject to very large uncertainty around future monitoring methods
	Not applicable or outside the scope of this project

GHG emissions (non-H_2) from new, standalone grey and blue hydrogen production are considered to be well-covered by existing regulation and reporting practices via the ETS and PI. The NAEI is likely to be able to access verified data for these emissions, and therefore the availability of relevant EFs is likely to be less of a concern (as these could be derived from ETS data).

The availability of data for **fugitive emissions of hydrogen** is likely to vary across the value chain, with more challenges for more diffuse sources due to the significant regulatory gap, for example in smaller combustion units in domestic and commercial settings and for transport by means other than pipeline. While there are some published estimates of fugitive emissions rates, these are subject to assumptions and high uncertainty ranges (or very low understanding of potential uncertainties). There is considerable research underway to improve the ability to measure hydrogen leakage, which could theoretically be used to improve leakage rates estimates across the value chain; however, this would require additional effort to implement these techniques in order to improve estimates for those areas unlikely to be incentivised by existing regulation, for example transport by means other than pipeline and hydrogen use in domestic and commercial settings.

NOx emissions from combustion of hydrogen are likely to be well-covered by existing regulation under the IED and EPRs for combustion in large installations (e.g. power, industry), but significantly more of a gap in smaller combustion units in domestic and commercial settings. Work underway by the COSH-AIR project is likely to improve understanding of the magnitude of this potential impact, which could inform requirements for future research.

Industrial facilities covered by IED/EPR are required to report on ammonia emissions. However, knowledge on the impact of fugitive emissions of **ammonia for use as a hydrogen carrier** across the value chain (including transport, storage) is considered to be underdeveloped and, while acknowledged by many stakeholders as a potential issue, its significance is not well understood.

Figure 3.1: Key UK project, policy, and regulatory milestones

	2022	*2023*	*2024*	*2025*	*2026*	*2027 – 2030*
Research studies/ projects	- Frazer-Nash report - JRC report	- MefHySto (Various, NPL) - Leakage Management in the Energy System Transition (SGN)	- COSH-AIR (Imperial) - COSH-AIR (University College London) - DECARB (Various, NPL) - GOTT (NPL) - Defra & EA Hydrogen leak detection techniques (NPL) - Multi Gas Detection (National Gas Transmission) - H100 neighbourhood trial - Tees Valley Hydrogen Transport Hub		- Digital Platform for Leakage Analytics (Cadent)	
Funding/ programmes			- First allocation rounds of the Transport and Storage Business Models	- Advanced Fuels Fund, SAF plants operational in >2025 - Net Zero Hydrogen Fund, --Strand 2 projects operational in >2025 - Hydrogen Allocation Rounds (HAR) 1, projects operational	- Hydrogen Allocation Rounds (HAR) 2, projects operational	- Hydrogen Allocation Rounds (HAR) 3-4, projects operational
Regulation/ policy		- UK Low Carbon Hydrogen Standard - Strategic policy decision on gas blending (up to 20%) - Hydrogen Strategy Delivery Update - Launch of Hydrogen Manufacturing Taskforce	- Consultation on Future System Operator’s role - Low Carbon Fuels Strategy - Zero emission HGV Infrastructure Strategy	- IEA Commodity balance requirement - Introduction of a SAF mandate - Launch of Hydrogen Certification Scheme	- Strategic policy decisions on hydrogen in heating - Review of UK Hydrogen Strategy	

4 Review of current NAEI

4.1 Introduction

In the NAEI 2024 submission (1990-2022 inventory estimates), the only emissions that will be included within the reported data that are associated with the hydrogen value chain are those from the production of hydrogen (mostly as an interim product) within UK installations such as refineries and petrochemical plant. In these instances, the origin data from operators is not sufficiently detailed to enable separate reporting of the emissions specific to production of hydrogen, but rather they are part of the installation-wide reported data.

There are no existing NAEI models that explicitly derive emission estimates from any aspect of the hydrogen value chain. New data streams and models will need to be developed to enable reporting of hydrogen value chain emissions within the future inventory reporting system. In the short to medium term the focus will be in developing the systems and models to report those emissions identified as priority areas (which are the subject of this report):

- Fugitive emissions of hydrogen across the hydrogen value chain (including emissions arising from production, storage, transport, transformation, and end use).
- Atmospheric pollutant (NOx only) and GHG emissions (N_2O) from hydrogen consumption, in domestic, industrial, transport, and power generation.
- GHG emissions from grey and blue hydrogen production - methodology update to account for carbon capture.
- Ammonia as a hydrogen carrier – NH_3 fugitive emissions from ammonia production, transport, and reconversion to hydrogen.

The emissions arising from the sources above will need to be reported in the following GHG and AQP inventory categories:

- 1A1: Emissions from the energy supply sector from fuel combustion associated with hydrogen production.
- 1A1: Emissions from the energy supply sector associated with the use of hydrogen in fuel transformation activities, e.g. production of ammonia or methanol as an energy carrier.
- 1A: Emissions from the combustion of hydrogen as a pure fuel, and/or hydrogen as a fuel as part of a gas blend within a wide range of economic sectors such as:
  - Stationary combustion in industry, commercial, public, residential.
  - Mobile combustion in road transport, non-road mobile machinery.
- 1B: Fugitive emissions[4] of GHGs, AQPs and hydrogen associated with the production, storage, transport (pipeline, tube trailer, other) and distribution of (i) pure hydrogen gas, and (ii) hydrogen-natural gas blends.
- 2B: Chemical process emissions of GHGs associated with hydrogen production and/or any fuel transformation process sources that are chemical in nature rather than combustion related.

Whilst the NAEI does not currently include any hydrogen-specific emission source methods, this section of the report will set out the details of analogous emission source methods, to indicate the likely data and modelling requirements to be developed for the hydrogen value chain. These

[4] Note that 'Fugitives' in IPCC inventory guidance comprises emission sources including: flaring, venting, process fugitives; these emissions cover both point source emissions as well as diffuse (e.g. leakage) sources.

are predominantly taken from emission sources relating to energy system production, transport, storage, transformation, and ultimate consumption of other gaseous fuels, e.g. natural gas.

4.2 NAEI standard approaches and protocols

The selection of future data sources for inventory reporting should be guided by existing data quality standards for national statistics. Currently, the NAEI applies an appropriate data hierarchy (described further below) which accounts for data quality and reliability.

Many NAEI methods apply standard approaches and protocols that the project anticipated will be relevant to future hydrogen emission source methods, including:

Emissions data hierarchy: In the derivation of UK GHG emission estimates for high-emitting combustion and industrial processes, such as power stations, refineries, petrochemical plant, operators typically report installation-wide emission estimates to the PI, and also report total CO_2 emissions to the UK ETS. The ETS data are third-party verified and hence regarded as higher quality data; therefore, in NAEI methodologies that use operator-reported data to derive CO_2 emission estimates, the ETS data are used in preference to PI data on CO_2. In these cases, the NAEI methodology typically uses the ETS data to derive a source-specific UK carbon EFs to apply to the best available AD; the AD may be derived from ETS (where the ETS has complete coverage of all UK installations in the sector) or from DUKES (where the DUKES data are more complete).

Where operators only report CO_2 to the PI, these data are not used within the NAEI. However, where operators report CH_4, N_2O, fluorinated gases (HFCs, PFCs, SF_6 or NF_3) or priority air quality pollutants (e.g. NOx, SO_2, NMVOCs) then these data are considered for use within inventory methods, often supplemented by other information from the plant operators to provide source-specific estimates.

AD hierarchy: In a handful of industrial sectors, the ETS scope includes all relevant installations across the UK; for example, all power stations, refineries, cement plant, lime plant and integrated iron and steel works report to the ETS. Where the sum of fuel use reported in the ETS differs from that reported in DUKES, the inventory agency may deviate from the UK energy statistics, but this requires case-by-case analysis to determine whether the DUKES data are errors for that sector only or are misallocations between sectors.

Data gap-filling: Operator reported data within the PI are often incomplete due to the reporting thresholds that are set by regulators; often a site will only report emissions for a small number of pollutants in the PI, as the other pollutants are BRT for that year. Similarly, for a given pollutant the reporting across all installations in that sector may be incomplete, e.g. with the less emissive installations not having to report pollutant estimates where the annual emission is BRT. In the NAEI methods, where pollutants are reported in some years, at some sites, as BRT then this doesn't mean that there were zero emissions; the inventory agency therefore gap-fills these BRTs with an estimate of the annual emissions, applying IPCC best practice techniques.

Spatial data reporting: The NAEI emission modelling must enable all outputs for NAEI users to be delivered, which comprises national-level data as well as sub-national emission estimates and emission maps. Therefore, the future reporting of hydrogen emissions will need to be spatially resolved. This is achieved using a range of methods and data, depending on the emission source and available information. For high-emitting installations where point source data are reported via the ETS or PI, then the inventory agency maps the spatial co-ordinates of the defined installation and allocates the emissions accordingly to that point source location. For smaller-emitting sources and area sources, which may also be regulated or may be small-scale units such as residential or commercial sector sources, then other methods are deployed. The NAEI spatial methodology report [27], updated annually, outlines the various methods employed to spatially disaggregate the NAEI emissions.

4.3 Hydrogen production

This section provides a methodology overview for hydrogen production activities, which is relevant to the following priority emission sources:

- Fugitive emissions of hydrogen from production.
- GHG emissions from grey and blue hydrogen production.

There are many potential production mechanisms for future hydrogen production in the UK, across a range of emissive and non-emissive (of fossil carbon) technologies. For all such production facilities there is scope for fugitive releases of hydrogen (and other gases) from storage facilities, pipelines, and associated infrastructure (flanges, compressors etc), process venting and/or flaring. It is envisaged that any new future hydrogen production based on fossil (or part-fossil) feedstock reforming and/or gasification process will have to also encompass Carbon Capture (Utilisation) and Storage (CC/U/S).

Where hydrogen may be produced via non-fossil-carbon emissive methods, e.g. electrolysis of water, then hydrogen fugitive emissions may arise from: start-up and shutdown venting, operational venting and leakage through the casing of the electrolyser. The emissions through the CC/U/S route includes pipework leakage and venting incidents [15].

4.3.1 Current UK hydrogen production: Emissions Reporting

There are existing hydrogen production installations in the UK, predominantly at refinery facilities, including Grangemouth and Lindsey oil refineries, as well as at a handful of petrochemical installations.

Where any of these installations may emit hydrogen gas directly to atmosphere (e.g. through venting, leaks), then these emissions are not currently regulated; there are no monitoring obligations for the operators of the UK refineries (or other sites) to measure and report hydrogen emissions.

There are existing regulatory requirements and mechanisms for the reporting of emissions of other pollutants associated with hydrogen production facilities. Emissions of carbon dioxide, methane, nitrous oxide, oxides of nitrogen (NOx as NO_2), SO_2, NMVOCs, particulate matter (including PM_{10}, $PM_{2.5}$ fractions) and many other air quality pollutants are all required to be reported as annual estimates (only if emissions on a given year above reporting thresholds) under the IED to the PI of the environmental regulator. The CO_2 emissions from fuel combustion and process sources on these sites are also reported within the UK ETS; source-specific reporting of emissions from hydrogen production is already reported by several UK installations within the ETS.

4.3.2 UK inventory methodology: Hydrogen production

The UK GHG inventory methodology for reporting of the emissions indicated above (non-hydrogen GHGs and AQPs) uses the ETS reported emissions for CO_2 directly and the PI data for other pollutants, as well as AD within DUKES and from the ETS. Additional EFs and fuel quality data are also provided to the UK inventory agency by the refinery sector trade association, Fuels Industry UK [28] (formerly the UK Petroleum Industry Association). The GHG inventory methodology is described within the National Inventory Report [29], Method Statement #1 (page 137 of the 2023 submission).

Consistent with the 2019 Refinement of the 2006 IPCC Guidelines for National GHG Inventories and the UNFCCC Reporting Guidelines, for installations where the emissions associated with hydrogen production are reported aggregated with emissions from other units (as is the case currently for UK refineries and petrochemical plant) the UK GHG inventory does not report the hydrogen production emissions separately; all GHG emissions from across UK refineries are reported in IPCC source category 1A1b Petroleum Refining, including those associated with hydrogen production.

As UK hydrogen production develops, including the (likely) development of standalone hydrogen production facilities, then the UK GHG inventory methodology for estimation and the reporting of emissions is anticipated to align with the requirements set out in the 2019 Refinement Volume 3 [30] for IPPU, Chapter 3 [31] (Chemical Industry Emissions), Section 3.11.

4.3.3 UK inventory data requirements: Hydrogen production

In order to generate GHG estimates consistent with the 2019 Refinement methodology, the UK inventory agency will require AD to become available on the annual UK production of hydrogen via all of the different emissive production pathways, i.e. per feedstock/technology type. This may become available via the reporting systems that will be needed to underpin future UK hydrogen commodity balance tables, which the DESNZ energy statistics team will be required to develop to report in line with IEA expectations from 2025 onwards.

Ideally the availability of highly resolved (per feedstock/technology) AD will be supplemented by installation-level reporting of GHG and AQP emissions via the UK-ETS and IED/PRTR mechanisms, as per current hydrogen production plant. This will enable the development of UK country-specific EFs for hydrogen production and a higher-Tier IPCC methodology to reflect the high level of accuracy that will be required for a (likely) future key category in the UK inventory.

4.4 Transport and storage of hydrogen

This section provides a NAEI methodology overview for hydrogen transport and storage activities, which is relevant to reporting of fugitive emissions from hydrogen transport and storage.

The future transport and delivery of hydrogen to storage sites and end users is anticipated to comprise a number of potential routes [32], including:

- Via new hydrogen-only pipelines and associated infrastructure, for pure hydrogen gas.
- Via re-purposing of the existing natural gas pipelines and associated infrastructure, for natural gas-hydrogen blends.
- Via tube trailers and associated transfer/storage facilities, as compressed hydrogen gas.

Hydrogen could be transported through a repurposed NTS and DN. The leakage from such systems includes emissions pipework leakage as well as compressors through seals or planned process venting and start-up purging.

4.4.1 Current UK hydrogen transport and storage: Emissions reporting

There is no current UK activity nor emissions reporting for any hydrogen transport or storage mechanism. The following sections therefore outline the equivalent systems used for natural gas transport, storage, and the associated emissions reporting within the UK inventory.

4.4.2 UK inventory methodology: Natural gas transmission and distribution

The UK natural gas transmission and distribution systems transport natural gas from various input locations (gas terminals, LNG terminals, import/export interconnector gas pipelines, biogas production/upgrading facilities) to end users across the industrial, commercial and residential sectors, via a network of high-, medium- and low-pressure pipelines and associated infrastructure. This gas transport generates GHG and AQP emissions from numerous sources including:

- Gas combustion at compressor stations on the network.

- Venting.
- Fugitive releases from pipelines, flanges, storage sites, compressors and other infrastructure.
- Gas slippage, e.g. at gas turbines.
- Post-meter leakage within residential and commercial facilities.

Across this scope of installations, infrastructures and pipelines there are numerous agencies involved in the industrial and environmental regulation of activities, and a resultant range of regulatory and data reporting obligations for operators to address. The UK inventory methods draw upon the best available data per source in each case. This is described in Annex E, which provides more detailed methodologies for some subsections of the hydrogen value chain (which are more complex and/or are anticipated to be more directly relevant to hydrogen).

4.4.3 UK inventory data requirements: Hydrogen transport and storage

4.4.3.1 Pipeline transport

The existing methods in the UK GHGI for methane emissions from natural gas transport via pipelines and for emissions at point of use provide a useful template for the data and methods needed to estimate emissions from future delivery of hydrogen via pipelines, either within hydrogen-only networks or as part of a natural gas-hydrogen blend. Key challenges to include:

- Completeness and consistency. Initial development of the hydrogen economy is likely to comprise a series of separate, discrete production-to-pipeline-to-end-user networks where the scope and approach to reporting will need to be defined and consistent across all sites/networks in order that complete, consistent data become available to the inventory agency.
- There is very limited research evidence to inform the development of an equivalent SLM for hydrogen, either in a bespoke hydrogen-only pipeline network or in a natural gas-hydrogen blend within existing pipeline infrastructure. Further, for several emission sources the existing SLM methods are simplistic and based on decades old gas leakage research.

4.4.3.2 Storage

Hydrogen could be stored in salt caverns as well as above ground storage facilities, such as compressed tanks. The examples for natural gas include onshore and offshore facilities. It is understood that the current plan for regulation of hydrogen storage is yet to be determined, see Annex E. Key challenges to address will include:

- Completeness of the regulatory framework to deliver data for large and small hydrogen storage sites alike on the annual storage, stock changes, as well as any regulation and reporting of estimated releases from routine and accidental activities, such as leaks from supply and storage infrastructure, from maintenance activities, venting.
- Completeness of scope and resolution of reporting from different regulatory mechanisms, offshore and onshore. Where installation-wide aggregate emission estimates are reported (as per IED/PRTR regulated installations), it will not be transparent regarding the completeness of scope of reported emissions; whether operators have included estimates of emissions from storage/ transfer may not be transparent.

The issue of estimating emissions from releases from storage also refer to the subsequent transformation of hydrogen to other energy carriers such as ammonia, methanol and the subsequent risks of releases from storage/ transfers at ammonia and methanol production, transfer and storage infrastructure.

4.4.3.3 Tube trailer transport

There is no current UK inventory source that is directly equivalent to hydrogen delivery via tube trailer. To derive an inventory methodology will require new data gathering mechanisms and to develop a method to reflect hydrogen leaks at compression/ filling stage and at decompression/ use stage. Key challenges will include how to gather data for such a disparate source including the need to gather data on the tube trailer fleet, assumptions re: mitigation, maintenance, operation etc.

Across the sector, the inventory agency would need to obtain data on the mass/volume of hydrogen annually delivered via this method as underpinning AD for any new method. Where the hydrogen is delivered either as pure hydrogen or as part of a gas blend, it is likely that the material properties will be required, e.g. density, volatility, in order that methods can be developed that reflect the different behaviour and thermodynamics of all gases/blends, at all stages associated with the transport of the fuel, across the range of seasonal temperatures across the UK.

4.5 Hydrogen use

This section provides a NAEI methodology overview for hydrogen use activities, including use in combustion in several sectors and use in transport, which is relevant to reporting of atmospheric pollutant (NOx only) and GHG emissions (N2O) from hydrogen consumption, in domestic, industrial, transport, and power generation.

4.5.1 Current UK hydrogen emissions reporting from hydrogen use

Combustion of hydrogen does not currently occur at a significant level in the UK. Where it does occur, hydrogen is one of many fuels being burned on an installation (e.g. a refinery) and the emissions are included within the aggregated operator estimates from across the installation, rather than as a separate process.

Hydrogen use in transport, using fuel cells, does not currently occur at significant level either and it is not currently reported in the NAEI.

4.5.2 UK inventory methodology: Hydrogen use emissions

The end use of hydrogen as a fuel for combustion across different sections of the UK economy will require the development of methodologies that are analogous to the many equivalent fuel combustion methods for other fuels as per the methods reported in Method Statements #1 (Energy industries), #3 (manufacturing and construction), #5 (other stationary combustion) in the NIR, including to address data sources and emissions to cover emissions from hydrogen used as a fuel within the industrial, commercial and institutional, residential and transport sectors.

The underpinning AD for all these estimates will be, as per other fuels, the DUKES commodity balance tables for hydrogen consumption across the economy, within energy industry sources, in fuel transformation and in final demand sectors. This underlying data will likely need additional modelling to determine the precise uses of hydrogen at a technology-specific level within each sector, for example to estimate hydrogen use in NRMM and across the vehicle fleet.

Emissions from road transport in the GHG and AQP inventories are obtained from a combination of activity and EFs data sources. The AD is typically obtained from the Department of Transport datasets that include traffic data, vehicle licensing statistics, ANPR and MOT data. Data on petrol and diesel fuels consumed by road transport in the UK are taken from the DUKES dataset published by DESNZ. The EFs are obtained from COPERT 5.4, EMEP/EEA 2019 inventory guidebook [33]. The model can potentially be modified in such way to account for similar type of activity and EFs data for the fleets that consume hydrogen as fuel.

With regards to emissions from power stations, the inventory uses AD on fuel consumption from DUKES, UK/EU ETS, LCP database, and carbon factors that are primarily obtained from the ETS data in combination with emissions factors derived from UK research and IPCC defaults (for non-CO_2). As discussed earlier for the refineries, similar type of data streams and models could potentially be developed in the inventory context to obtain activity and emissions data for combustion of hydrogen. This could also be extended for process industries, e.g. iron and steel, glass, where hydrogen may play a role in the future.

4.5.3 UK inventory data requirements: Hydrogen use emissions

Key challenges related to the inventory data requirements for hydrogen use will include:

- Deriving a complete AD set across all source categories and technologies for mobile and stationary combustion, for both pure hydrogen and also for natural gas – hydrogen blends at different percentage shares.
- Development of accurate, representative EFs for pollutant emissions from hydrogen combustion in each use case; whereas in industrial installations it can be expected that routine monitoring by operators will provide accurate UK emissions data, for smaller-scale combustion units (e.g. in residential and commercial sectors), the current evidence base is extremely limited to estimate the emissions of priority pollutants (e.g. NOx) from hydrogen and gas-hydrogen blends across representative UK installations.
- To obtain a sufficiently detailed hydrogen AD set that enables high resolution to track the fate of hydrogen for use as a feedstock, in transformation processes (e.g. to ammonia, methanol) and also for use in fuel cells, rather than as a combustion fuel.

4.6 Hydrogen transformation to ammonia

4.6.1 Current UK Hydrogen transformation to ammonia reporting

Current NAEI industrial process emissions of ammonia are derived from plant operator estimates reported to environmental agencies under regulatory systems, such as the IED and the UK EPR. Although this does not include hydrogen transformation to ammonia, this operation already occurs in the UK with associated emissions to atmosphere reported within the ETS and the PI. There are several ammonia production plants across the UK (although most have been recently closed or mothballed). In all cases the inventory agency receives fuel use AD and emissions data from the ETS, as well as total installation emissions from the PI. There are multiple processing units within the boundary of the permitted installation and hence to obtain data specific to the ammonia production plant requires that the inventory agency to request additional, supplementary (to ETS, PI, etc.) information direct from the operators and, in some cases, from the regulators.

For example, the information on annual production of ammonia per installation is only made available to the inventory agency through direct requests; these data are not routinely available through any established reporting system via the environmental regulators nor ETS.

4.6.2 UK inventory methodology: Hydrogen transformation to ammonia

Across UK ammonia production installations currently in operation, all but one of the sites comprise an installation to generate a hydrogen stream (with associated CO_2 emissions reported) and an ammonia production installation. One UK installation generates ammonia directly using a hydrogen stream from a nearby installation.

In all cases, the inventory methodology is to access the most highly resolved emissions data available, specific to the ammonia production plant, and to aggregate those reported emissions, with data validation checks conducted to compare annual emissions against ammonia production data per installation. The emissions data are then reported via the NAEI database, aggregated across all UK plant. As all installations are permitted sites that report to the ETS and PI, the spatial disaggregation of the emissions for the purposes of emissions mapping and sub-national outputs is managed via the NAEI point source database.

One point of note is that the use of natural gas as a process feedstock in the ammonia production sector is regarded in energy statistics terms as a Non-Energy Use of natural gas, as the gas is being used as a feedstock to a chemical process. There is also a natural gas feed to use as a fuel to heat the chemical process, and this component of gas use is reported as a fuel use within the chemical sector. The inventory agency obtains information annually from operators regarding the use of natural gas (i) as a fuel, and (ii) as a feedstock, and uses these values accordingly within the NAEI natural gas balance; this may lead to deviations from the DUKES natural gas commodity balance, and if so, this is reported in the NIR annexes.

4.6.3 UK inventory data requirements: Hydrogen transformation to ammonia

Hydrogen is expected to be generated and, in some cases, subsequently transformed to other energy carriers such as ammonia or methanol. There are numerous equivalent transformation processes and chemical industry sites where similar processes are already conducted in the UK, regulated and reported within the UK NAEI inventory.

Storing and transporting hydrogen has very high-pressure requirements, making it both difficult and hazardous to store/transport as a fuel. Using NH_3 as a hydrogen carrier is an option and may be more suitable for long-term storage and utilisation due to its high volumetric density and associated low-storage losses compared to hydrogen. The transportability of NH_3 is especially attractive to industries reliant on long-distance transportation, such as maritime shipping.

It is anticipated that the UK inventory methodology for hydrogen transformation to ammonia will be informed by existing data sources (i) DUKES and (ii) industrial operator reporting via extensions to existing reporting mechanisms such as ETS, IED/PRTR; there are several ammonia and methanol plant operational in the UK and Europe that already report emissions via these mechanisms. As indicated above, AD for ammonia production is only obtained through direct requests to installation operators (as not covered by any regulatory reporting), therefore this is likely to be the most challenging area to be addressed.

4.7 Ammonia transport and storage

If ammonia use as hydrogen carrier becomes an important part of future hydrogen economy, there is a risk that fugitive emissions of ammonia, not only from production facilities (hydrogen transformation to ammonia) but through transport, storage and other ancillary activities (e.g. compression/filling, decompression) could be significant. As indicated in Section 3.3.3 there is little research in this area and therefore the significance of such emissions is still unknown.

4.7.1 Current UK ammonia transport and storage reporting

Fugitive emissions of ammonia from ammonia transport and storage are not currently reported in the NAEI. The AQP inventory does report ammonia emissions from transport sources, but these refer to emissions arising from combustion processes (e.g. NOx reduction in road vehicle catalytic converters).

4.7.2 UK inventory methodology: ammonia transport and storage

As there are no current reporting mechanisms to gather information on ammonia transport and storage fugitive emissions, to develop an inventory methodology would require new data gathering and reporting mechanisms and methods to estimate fugitive emissions along the value chain (when measured data reporting, e.g. point source, is not viable).

4.7.3 UK inventory data requirements: ammonia transport and storage

Similar to the needs for hydrogen fugitive emissions in transport and storage, the data needs for ammonia fugitive emissions reporting are likely to include:

- Across the sector, the inventory agency would need to obtain data on the mass/volume of ammonia annually transported and stored, as underpinning AD for any new method.
- EF would need to be developed to support these stages of the value chain as not covered by regulatory reporting.

The anticipated challenges to enable reporting of ammonia fugitive emissions include:

- Completeness of the regulatory framework to mandate reporting of ammonia AD and fugitive emissions across production, transportation, storage, and conversion back to hydrogen.
- Completeness of scope and resolution of reporting.
- Development of EFs for those areas not covered by reporting.

5 Development of inventory data and methods

5.1 Introduction

This section sets out our current understanding of the inventory methods and data that will be required in the future to enable the UK NAEI to deliver emission estimates of GHGs and AQPs from all sources across the hydrogen value chain. In many instances, as the hydrogen economy is still in its very early stages of development, this research is an opportunity to set out the ideal UK national inventory system requirements that DESNZ should consider in order that MRV systems are designed, resourced and implemented such that the UK has a strong evidence base in the future to accurately report the emissions and track the impact of the hydrogen economy.

Where applicable this report sets out an initial proposal for the key developments that are needed to enable these methods to be implemented, i.e., to set up data gathering systems, regulations or other reporting mechanisms, data quality checks/ verification systems across UK regulatory, research and statistical agencies. The report also flags the remaining gaps in knowledge and/or where it is not clear as yet how the regulatory framework will operate, which organisation will have responsibility, and the required resources to implement necessary actions.

5.1.1 Selecting an appropriate approach

Note that, while approaches are proposed here based on information available at the time of writing the document and the expert judgement of the project team, the final decision on implementing inventory methods will be with the Inventory Agency and NAEI governance mechanisms (i.e., the National Inventory Steering Committee) and are likely to evolve as the data landscape develops.

In setting out proposals across all source categories, the project team considered over-arching inventory good practice to prioritise effort towards the data and methods that will be needed for the likely key categories (albeit there is uncertainty regarding our selection of ‘key categories’ to focus on, across an industry yet to develop). For some source categories there are several method options, with more simplistic Tier 1 methods likely available to implement in the short term, to address completeness, with subsequent improvements to develop higher-Tier methods to deliver inventory estimates that are more accurate and representative of UK circumstances. For some source categories it may be pragmatic to await the development of UK data resources and then deliver a more accurate[5] Tier 2 or Tier 3 method and accept a short period where the UK inventory is not complete for all sources.

5.2 Cross-cutting issues and impacts

5.2.1 Impacts to NAEI models

The new inventory methods will need to be integrated within the wider NAEI model suite for onward inventory reporting and new data quality checking mechanisms will need to be developed, for example to develop a hydrogen mass balance check, comparing UK NAEI AD

[5] The 2019 Refinement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories notes that “Tiers 2 and 3…. are generally considered to be more accurate on condition that adequate data are available to develop, evaluate and apply a higher tier method”(6).

against UK energy statistics. For many new hydrogen economy source categories, new standalone inventory models will need to be developed, whilst for other source categories it may be practicable (and preferable) to integrate the new method requirements within existing NAEI models; the project team has outlined the linkages of the NAEI models, per source category, to consider in future work.

For any new source to be included, it will be necessary to review the scope and boundary of the method and EF applied to make sure that there are no emissions lost between stages, for example the point of handover between the hydrogen transport process and a storage facility.

While the reporting of hydrogen will require careful consideration of the points outlined below, this is not a new challenge, as the NAEI team has added new fuels and activities to the Inventory in the past. The complexity is anticipated to lie in the characterisation of these activities, selection of appropriate data sources, the definition and communication of these requirements, and the establishment of an appropriate system to deliver that information.

5.2.1.1 Granularity and resolution

For all the source category methods outlined here, there will be a requirement to determine the optimum level of resolution for conducting the calculations which will typically be defined by the availability of AD and EFs that can be applied at as high a level of resolution as needed to generate emission estimates that are representative of UK circumstances. Ideally the calculations should be structured such that key step-changes in the EFs can be reflected in the inventory methodologies, for example:

- To enable methods to be developed that enable specific modelling for sub-sources, e.g. different component parts of a gas supply network.
- To estimate hydrogen emissions from source categories at a sufficiently detailed level such that e.g. production or combustion using different combinations of technology, thermal capacity and fuel/ feedstock types can be individually modelled.
- To estimate emissions from sources using pure hydrogen gas separate from sources using hydrogen gas blends (e.g. with natural gas).

Where there are current data gaps but an acknowledgement that future research will be needed to furnish a greater evidence base at higher resolution to achieve greater accuracy (especially for a key source category), it is pragmatic to design the inventory source category calculations to be future-proofed, i.e. conducting the calculations at a higher level of resolution in anticipation of the research into AD and EFs development to populate the model.

5.2.1.2 Data processing

Cross-cutting data processing issues across the NAEI-wide model data flow include:

- For all hydrogen source categories that draw upon operator-reported estimates from high-emitting installations, the pre-processing NAEI models used to process ETS and IED/EPR data into NAEI-ready data, labelled with NAEI source codes, activity codes and pollutant codes, will be the logical starting point. Development work will include analysis and documentation of installation permit information and environmental reporting materials (e.g. ETS emission monitoring plans) to prepare NAEI point source data resources to enable hydrogen source category data processing.
  - Note that as well as deriving high quality UK *emissions* data for a higher tier methodology, the data processing of ETS data will also deliver high quality *AD* for several hydrogen source categories, to augment DUKES data.
- Further, for blue hydrogen production the ETS will provide the underpinning evidence, third-party verified, regarding the carbon capture installations, the emissions and losses across

the pipeline transport stage, and the measurement evidence for the geological storage of captured CO_2.

- Where literature EFs (for any NAEI pollutants) are available for application within hydrogen source category models, these EFs may be processed within the NAEI EFDB processing system, which comprises an input spreadsheet for documentation of the origin EFs and units, for subsequent conversions (e.g. to ensure consistent energy units for use across NAEI models).
- Whilst individual source category methods may be based on a range of primary and secondary data sources, across the inventory the methods will ultimately be reliant on access to a complete hydrogen commodity balance from DESNZ, as for all other UK fuels. To provide AD required for specific emission source categories, the hydrogen commodity balance will need to be highly resolved, complete and report data on fuel transfers into and out of the hydrogen commodity balance to reflect fuel transformation and blending activities, including:
  - Hydrogen production data resolved by technology/ feedstock (e.g. electrolysis, SMR, ATR).
  - Hydrogen consumption as a fuel or feedstock per economic sector: as a pure fuel and as a blended fuel.
  - Hydrogen transfers out to blended fuels (e.g. into natural gas pipelines) and their consumption per economic sector.
  - Hydrogen transformation into ammonia, methanol (and other energy carriers) and data on their ultimate consumption per economic sector.
  - Data on hydrogen losses from transport, storage and other activities.

5.3 Generalised ideal data reporting system and data hierarchy

Though data sources and methods will vary according to the emissions source category in question, there are common reporting systems and datasets that would enable regular, high quality data supply to the NAEI. These systems are considered to be a ‘reasonable ideal’ for the UK to aim for in the medium to long term, based on existing legislation, regulation, and reporting practices. These systems and datasets include:

- A detailed and highly resolved hydrogen commodity table prepared by DESNZ Energy Statistics (see Section 5.2.1.2 above).
- Installation-specific data from the ETS for hydrogen production emissions, with measurements for carbon capture volumes (for blue hydrogen production).
- Installation-specific data for hydrogen consumption AD at large installations (this not covered by UK ETS so other reporting mechanisms will need to be established).
- Measured NOx releases for all sites under the IED, or values that have been calculated using consistent methods, assumptions and EF.
- Measured ammonia releases for all sites under the IED and/or PRTR, or values that have been calculated using consistent methods, assumptions and EF.
- Measurement of hydrogen fugitive emissions, including leakage, from new hydrogen pipelines and from blending in the existing gas transmission and distribution system, or model that has been calibrated with measurements.
- Well developed, country specific hydrogen fugitive EFs across value chain stages other than pipeline transport.
- Well developed, country specific EFs for combustion of hydrogen NOx emissions in all applications across the value chain, particularly for diffuse transportation and consumption activities.

- Well developed, country specific EFs for ammonia fugitive emissions across value chain stages, particularly for diffuse transportation, storage, and consumption activities.

The establishment of this ‘ideal’ reporting system and datasets would require:

- The majority of the hydrogen value chain to be covered by regulation with clear boundaries and guidance, with no significant gaps between regulatory bodies.
- Reporting requirements under applicable regulation to be of sufficient granularity, based on measurement where possible or well-developed calculation methods, for AD and EFs.
- Acknowledgement across the value chain of the potential significance of hydrogen fugitive emissions, with measurement and reporting requirements in place.

5.3.1 How far are we from this ideal?

Some of these ‘ideal’ data reporting systems are already in place in the UK, while others will likely take additional time and resource to develop. This is assessed in the following table.

Table 5.1: Data reporting system readiness

System/ dataset	Readiness	Priority area*			
		1	2	3	4
1 – Detailed commodity balance	It is in DESNZ' authority to develop this, but is likely to require significant additional effort	X	X	X	X
2 – Hydrogen consumption AD for large installations	Not covered by UK ETS when hydrogen used as a fuel as no CO2 emissions occur. Likely to be addressed by DESNZ Energy Statistics hydrogen commodity balance development		X	X	
3 – Hydrogen production emissions from ETS	Already in place (grey and blue)	X			
4 – NOx emissions at IED sites	IED sites are required to report NOx. However, there are not yet consistent methods or EFs available to installations			X	
5 – Ammonia emissions at IED sites	IED sites are required to report NH3 emissions. However thresholds apply				X
6 – Measurement-enabled model for hydrogen leakage from pipelines	Actively being worked on by industry, but still in early stage		X		
7 – Hydrogen leakage rates across value chain	Starting to be addressed by research but still in early stage		X		
8 – Country specific EFs for hydrogen combustion across value chain	Starting to be addressed by research for some value chain steps. For some applications, opportunity to take learnings from early demonstration projects. Other applications likely to need further research.			X	
9 – Ammonia leakage rates across value chain	Topic in need of further research				X

*1= CO2 from blue/green production, 2= fugitive hydrogen emissions across value chain, 3=NOx and N_2O from hydrogen combustion, 4= fugitive ammonia from use as hydrogen carrier

Legend

Green	Already in place, high level of readiness
Yellow	Already in place, however further improvements needed, medium-high level of readiness
Amber	Not in place/ at early stage, medium level of readiness
Red	Not in place and would require further research on feasibility, low level of readiness

5.4 Inventory data and methods for prioritised areas

Inventory data and methods for the prioritised areas are outlined in the subsections below.

Recognising the varying readiness levels of the 'ideal' data reporting systems and datasets, where the project considered that there would be value in implementing an interim approach to improve the completeness of the inventory (where such methods would be unlikely to be immediately superseded – see Section 5.1.1), the project team has developed approaches for what is felt to be reasonable in the short to medium term based on research and engagement.

In the interest of improving the completeness of the NAEI, this project identified **initial approaches** that could be taken to include the source in the inventory and improve its completeness. However, it is recognised that these approaches are likely to have limited accuracy, with limited understanding of potential uncertainties.

This report has proposed **improved approaches** that would take advantage of data from upcoming research projects and/or opportunities to utilise measured or and/or installation-level data. It is anticipated that these methods could result in better approaches and/or higher tier reporting but are speculative at this stage. The report has outlined these to proactively identify data supply options that could be pursued by DESNZ.

In some cases, it may be possible to bypass the initial approach and jump straight to the use of an **improved approach** by the time the source reaches a significant level in the UK. This report has added commentary in the subsection 'assessment of approach' under Section 5.4.1.1 and 5.4.2.1 along these lines.

Annex F provides an indicative data map for the approaches described in this section (5.4).

5.4.1 Hydrogen fugitive emissions

Many of the required routine (annual) data reporting mechanisms needed to underpin fugitive emission estimates are as yet undeveloped, whilst other research and beacon projects that will test and develop measurement and leakage estimation techniques and models are yet to be defined, funded, and delivered (See Section 3.3.2.1 for details).

5.4.1.1 Initial approach

An initial approach for including fugitive emissions from hydrogen production, transportation, storage and use in the UK GHGI as a memo item would be to utilise DESNZ Energy Statistics figures (which would require the collection of new data beyond existing reporting practices) and apply fugitive emissions rates published by Frazer-Nash (2022). The report includes 50% (central case) and 99% (reasonable maximum) fugitive emission rates. The 50% value could be used for calculating fugitive emissions of H_2, with the 99% value used as an indication of uncertainty.

This approach has significant limitations, as outlined below, and may be superseded with improved data and/or assumptions by the time that fugitive emissions from the hydrogen economy reach a significant level.

Activity Data

It is anticipated that the most suitable data source for collecting AD for hydrogen production, transport, storage and use is DESNZ Energy Statistics. It is our understanding that DESNZ Energy Statistics are awaiting finalised guidance from the IEA on hydrogen reporting (which will be required by 2025). A draft of this is the hydrogen commodity balance provided by DESNZ Energy Statistics, which is available in Annex A. There is uncertainty as to the level of granularity that will be required by the IEA and how this might align to the Inventory requirements; initial commentary, based on the draft commodity balance, is provided in Annex A. A high level of feedstock and technology resolution for each UK hydrogen production pathway will be needed to enable complete and accurate GHG emissions estimates and to enable the inventory agency to avoid the risk of double counting of emissions within the national inventory, e.g. by duplicating emissions already reported by refineries and petrochemical plant operators.

For blue hydrogen production, this data could be cross-checked with information reported to the ETS (where reported). Also, it could be cross checked with initial hydrogen production values from innovation projects funded under the Net Zero Innovation Portfolio, which would be reported to DESNZ Energy Innovation teams.

EFs and assumptions

Based on currently available information, it is considered that initial fugitive emission rates could be taken from the Frazer-Nash report. These values are generally based on expert judgement, assumptions from applicable standards, and modelling.

EF would be based on the average fugitive emission rates per sub-source from the Frazer-Nash report; these would be applied to AD from DUKES that the project envisaged will be available in units of mass, energy and/or volume. Where needed, conversion factors (e.g. densities, NCV and GCVs) for hydrogen and blends will be obtained either from DUKES or from the gas industry directly. The application of these assumptions would require the DESNZ Energy Statistics Data is collected with at least the granularity provided in the Frazer-Nash report.

Model requirements

This simplistic top-down (from energy statistics) method doesn't draw upon any information currently used within the NAEI model suite and hence will require the development of a new standalone NAEI model. Many of the features and functionality required are similar to those applied within current NAEI models, including AD models (which translate DUKES commodity balances into NAEI source-AD) and the gas main model (which models gas leakage from the natural gas transmission and distribution network, using information from DUKES, ECUK, National Grid and the operators of Gas Distribution Networks – GDNs).

Depending on the approach taken by DESNZ to manage the fuel transformation (hydrogen to ammonia) and transfers (e.g. hydrogen gas transfers into the natural gas network), there are likely to be outputs from this model into other models (i.e. the natural gas activity model, the chemical feedstock model) and/or inter-model consistency checks (i.e. to ensure no gaps or double-counting in the NAEI). Further, the work to develop a new hydrogen AD model may well necessitate the addition of new lines of data within the cross-cutting model that processes UK fuel characteristics (i.e. NCVs, GCVs, densities).

If this initial approach is implemented, it needs to be kept simplistic to minimise waste of resources as the UK will then need to move towards development of higher tier methods once better data becomes available, to have a better assessment of uncertainty.

Once the AD is derived per NAEI *source code – activity code* combination, the model would simply apply the Frazer-Nash report factors:

$$\textit{Fugitive emission}_{\textit{Source A}} = \textit{AD}_{\textit{Source A}} * \textit{Leakage factor}_{\textit{Source A}}$$

Assessment of approach

The approach described in Section 5.4.1.1 would allow the reporting of fugitive emissions of hydrogen, thereby improving the completeness of the GHGI, however is considered to have relatively low accuracy and high uncertainty. The 50% and 99% percent confidence fugitive emission rates from Frazer-Nash are generally within one order of magnitude, with a notable exception of emissions from the national transmission system (which is already subject to high uncertainty for natural gas). A notable limitation of this approach is that the Frazer-Nash report is based on assumption of 100% conversion in pipelines, which would limit its suitability for hydrogen blending.

While it is within DESNZ Energy Statistics' institutional powers to collect the above-listed AD, this exceeds current reporting practices and would likely take time and resource to implement. To maximise the resource efficiency and value for money for the UK Government, it is worth considering waiting to implement this collection process until IEA Guidance on hydrogen reporting has been released.

By the time fugitive emissions of hydrogen are likely to be occurring at a significant scale, improved assumptions or data sources for hydrogen leakage may be available, which would supersede this method.

5.4.1.2 Improved approaches

Improved approaches to reporting fugitive emissions of hydrogen could take several routes, most/ all of which will require the ability to **measure hydrogen leakage** – either for the development of average leakage rates that could be applied across the value chain, or for the direct use of measured leakage data in the inventory.

There is a significant amount of work underway to build the capability to measure leakage of hydrogen (see Section 3.3.2.1), though this is focussed on certain applications (e.g. leakage from pipelines in the distribution network). Successful delivery of these projects could lead to improved values for average leakage rates for certain components/ applications; this would be an improvement compared to average fugitive emission rates outlined in the initial approach, which are primarily modelled or based on expert judgment.

In addition, higher tier methods will likely take a more detailed approach to developing the underpinning AD, e.g. to seek more granular data from the gas supply industry on AD and/or modelled leakage from different sub-components of the pipeline and tube-trailer supply network infrastructure.

Separate methods will need to be developed for the different source categories across the hydrogen value chain, as described below.

To estimate fugitive and venting emissions from within the boundaries of installations that are either **producing hydrogen** or using it as a **fuel or feedstock**. This report has grouped these sources together as the project team envisaged that such installations will fall under one or more of the existing MRV mechanisms for UK regulated industrial sites (i.e. reporting within the UK ETS and/or within the EPR/IED annual reporting of emissions to the pollution inventories of UK environmental regulators). For these sources, developing higher tier methods will rely on accessing operator-reported data per installation, from either measurements or calculated estimates using monitoring and reporting protocols agreed by the regulatory agency. The discussion below outlines the potential features and options.

Where it is impractical to obtain discrete estimates for emissions of pollutants specific to fugitive and venting sources from all UK installations, it may be pragmatic to accept that the data resolution is insufficient and not to derive a separate estimate from fugitive sources, but rather to accept that the fugitive emission sources are included within the reporting of other sources (e.g. under the transformation and/or combustion process reporting for those sites).

In that instance, the inventory agency and DESNZ may need to progress periodic research and consultation with operators and regulators to secure sufficient evidence and data transparency to justify that there isn’t a reporting gap in the inventory, and that fugitive emissions are indeed included within the operator-reported installation estimates.

It is likely that fugitive emissions reporting per installation may only be feasible/ economic for a sub-set of the (larger) installations. Good practice data gap-filling techniques may well be needed to include estimates for non-reporting sites,

Data processing will in part be efficient to conduct within existing NAEI models such as the Regulators Inventory Data Base (RIDB) and the EFs Data Base (EFDB) but will also require development of new standalone hydrogen production and hydrogen combustion models.

Separate estimation methods may be applicable for instances of leakage of pure hydrogen gas or from hydrogen gas blends.

In the initial phase of developing and testing these methods, a key information resource is expected to be data from the leading clusters/ projects that are first-movers, and all of the underlying environmental impact assessments, applications to operator (submitted to regulators as part of the permitting process under IED/EPR). The model will need to ultimately be developed such that it can be maintained through regular annual data access.

Higher-tier methods to estimate fugitive and vented emissions from the **gas supply and storage networks** will likely necessitate the gathering of significant new information to deliver a highly granular view of activity and emission sources across: pipelines, associated infrastructure (compressors, flanges, above ground installations, pig traps, compression and decompression stages, tube trailer systems), from maintenance activities, incidents, theft etc. up to the point of delivery to end users.

Methods will need to be developed to cover transport and storage of pure hydrogen and hydrogen gas blends, including gas compositional data and physical properties (such as density, volatility, NCV, GCV). A separate (but perhaps similar) model will also be needed to generate estimates of venting and leakage from the transport and storage of each hydrogen energy carrier, such as ammonia and methanol.

The range of calculations to be performed cannot be defined at this stage; there are too many unknowns at this point regarding how the transport and storage of hydrogen will develop in the UK. It is likely that models that are designed and populated annually similar to the GDN SLM model for natural gas leakage will need to be developed, which will infer that a considerable research programme will be needed to improve the understanding and characterisation of hydrogen delivery systems, over and above the initial expert judgements and limited measurement evidence base that is available to date, e.g. within the Frazer-Nash report.

Similar to the production/combustion points above, the initial model development will ideally draw upon evidence from leading clusters/ projects, but the annual model updates should be designed to operate based on routine annual operator reporting systems as far as practicable.

5.4.2 Hydrogen combustion and hydrogen fuel cells

The use of hydrogen has been considered for combustion in power, industry, domestic and commercial sectors, as well as to deliver power via hydrogen fuel cells; fuel cells are not emissive, whereas hydrogen used as a conventional combustion fuel will generate a range of pollutant emissions to atmosphere.

Regarding NAEI method development, there are two methodologies that will need to be developed in parallel: one for large, regulated combustion/industrial installations and one for smaller units across a range of sectors including residential, commercial and public. These will demand different modelling approaches and both methods can draw upon similar data structures and NAEI models used to estimate emissions from other UK fuel combustion.

For **high-emitting, regulated combustion and industrial installations,** NOx and other pollutant emissions arising from combustion of hydrogen as a fuel will be reported by operators to the regulatory agency pollution inventories, and will be pre-processed within the existing NAEI RIDB, to then input estimates per sub-sector (e.g. power stations, refineries, petrochemicals etc.) within a new hydrogen combustion model. As with other NAEI sources (and e.g. for hydrogen production site estimates), where there are non-reports of NOx due to the installation annual emissions falling BRT, good practice gap-filling techniques will be applied to generate complete estimates across all UK sites. As these data are reported per installation, the spatial allocation of emissions is straightforward to these point source locations, as per the core NAEI point source emissions mapping processes. Noting that these operator-reported emissions are typically derived from stack emissions measurements (either CEMS or periodic discrete sampling and analysis), the estimates will be associated with a better understanding of uncertainty.

For **lower-emitting, non-regulated sectors**, the methodology will be based on DUKES AD per sector and modelling using EFs. The level of data resolution to perform these calculations is not yet clear and the evidence base to inform pollutants EFs is extremely limited given the nascent industry sector and lack of research and in-site testing of the wide range of combustion units and hydrogen gases/ blends that may ultimately service the needs of commercial, institutional and residential end users to deliver space and water heating, cooking and so on. To develop accurate estimates will warrant a significant investment in:

- Research to derive best AD estimates of hydrogen use per sector, per technology/ unit type.
- Research to conduct emissions tests across a representative range of fuel-technology combinations in order to develop EFs at a suitable level of detail and accuracy to apply to the AD.

Further, to develop spatial emission estimates for the smaller-scale (non-point-source) emission sectors, further work will also be required to gather either spatially resolved AD (e.g. hydrogen meter-point data) and/or proxy datasets (e.g. building energy performance data) and to develop sector-specific mapping grids.

Both of the above methods will ultimately be based on the new DUKES hydrogen commodity balance in order to ensure that the NAEI can deliver complete emission estimates at the level of resolution required for inventory reporting.

In the development of these methods, it may be pragmatic to initially deliver a simpler, more aggregated emissions model and then develop further source (per fuel/technology combination) estimates as the research evidence emerges.

Discussions with leading researchers have highlighted the complexity of the subject matter, whereby different research teams globally adopt different standard practices/ protocols to develop EFs for hydrogen combustion. This is in part due to the very different combustion gas composition when deriving EFs for hydrogen fuel compared to the (well-documented) natural gas fuel combustion. Flue gases from hydrogen combustion have typically much higher moisture content and higher oxygen content (due to a need for higher excess air inputs for hydrogen combustion). This is an area for DESNZ to consider as regards communication and co-ordination of the necessary research effort to develop representative EFs for the NAEI.

5.4.2.1 Initial approach

For NOx emissions from installations that fall under the IED, this will be reported to the environmental regulators in their pollutant inventories and therefore values can be taken from there.

For NOx emissions from other sources, an initial approach would be to utilise AD from DESNZ Energy Statistics figures (which would require the collection of new data beyond existing reporting practices) and EFs from the EMEP/EEA 2023 Guidebook. The Guidebook provides EFs for hydrogen combustion and covers use in gas turbines, internal combustion engines, heavy goods vehicles, aircraft, maritime shipping, residential domestic boilers and commercial heating boilers [33].

Emission factors

Initial EFs could be taken from the EMEP/EEA Guidebook (2023) [33]. In some cases, these are the same as for natural gas or other existing fuels. It is noted that there is a very limited EFs evidence base for emissions from hydrogen combustion currently and applying the rudimentary EMEP/EEA Guidebook EFs is only an initial stopgap for completeness and 'order of magnitude' accuracy, until more sampling and analysis of hydrogen combustion flue gases is evident to derive more accurate, representative EFs for UK fuels and technologies.

Model requirements

As noted above, a new model to derive hydrogen AD per source category will need to be developed, derived primarily from DUKES but conceivably also with other data inputs, e.g. from UK ETS. Emission estimates from high emitting permitted installations that report to environmental regulator pollution inventories will be in part pre-processed via the RIDB and then within industry sector-specific models. The NAEI data processing for small-scale combustion sources across sectors including commercial, institutional, public and residential sectors could be handled via existing NAEI models, e.g. through the addition of EFs pertinent to hydrogen combustion source-activity (per technology, for pure hydrogen and fuel blends) combinations via the EFDB model.

Improvements, e.g. to derive more accurate EFs per fuel and technology type, could then be implemented as improvements to AD resolution (in the new hydrogen AD model) and EFs for UK combustion fuels/units become available. Priorities for improvement would likely be those sectors that exhibit the greatest consumption of hydrogen and a range of combustion units with potentially varying combustion performance.

Assessment of approach

The approach described in Section 5.4.2.1 would allow the reporting of NOx emissions from hydrogen use, thereby improving the completeness of the GHGI, however is considered to have relatively low accuracy and a low understanding of uncertainties for non-regulated sources. If this approach were implemented, the EMEP EFs should be updated as quickly as possible to more accurate EFs, for example from the COSH-AIR study (see Section 5.4.2.2 below).

5.4.2.2 Improved approaches

Activity data improvements

The project noted that NOx emissions from hydrogen combustion are sensitive to a wide range of parameters including fuel type (pure hydrogen or various hydrogen-natural gas blends), thermal capacity and control technology of the combustion device. Hydrogen-ready combustion units for most sectors are not readily available in the market, and there are very limited emission measurement tests to date, globally, to explore the range of combustion and emissions performance of units already available.

The accuracy of the emission estimates from hydrogen combustion will, over time, greatly improve as the granularity of AD per fuel and combustion unit type becomes more readily available alongside an increase in research to derive representative EFs.

It is envisaged that as the hydrogen economy develops, there will be a need for DESNZ to conduct surveys and research studies to gather data from across all economic sectors using hydrogen fuels, to understand the AD at a high level of resolution across units for space heating, water heating, cooking etc, within the commercial to residential scale of combustion units.

This will then enable NAEI models to be developed that better-represent the hydrogen fuels combustion, performing the emission calculations per pollutant at a more highly resolved level, applying EFs that are more accurate per sub-source, to drive down overall uncertainty and/or improve the understanding of uncertainties.

Emission factor improvements

Potential sources of EFs improvements could include:

- Imperial College contributions to the COSH-AIR study (see Section 3.3.3 for more details).
- DESNZ Innovation programmes, e.g. the Industrial Hydrogen Accelerator Programme. There are no clear measurement plans for NOx yet in place for these projects based on published feasibility reports 34, but this is often acknowledged as an issue to address in demonstration phase. Note that while this report considers this suggestion to be reasonable, it is fairly speculative as the project team has not confirmed with DESNZ Innovation teams whether these values are likely to be reported and made available.
- Village or town level hydrogen usage trials (e.g. H100) could potentially be a source of some NOx data for use in domestic and commercial appliances, though it is not clear what measurements may be undertaken; projects are still subject to a government decision on whether to proceed. This suggestion is also fairly speculative as the project team did not had confirmation within this project as to whether NOx will be monitored in these trials.
- Reported NOx from first plants starting operation, through established reporting requirements to regulatory bodies (e.g. IED/PRTR covered installations).

Model requirements

Per the previous sections, the project team envisaged that current NAEI models will be extended to accommodate the new data streams from both high emitting permitted installations (RIDB) and to impute EFs from a new range of small-scale hydrogen combustion technologies/sectors alongside a new hydrogen AD model.

In some high-emitting industrial applications (e.g. iron and steel production), there may be a need to redesign existing NAEI models to enable new information on emissions from hydrogen-fired units to be integrated within the overall data flow; these details will need to be assessed and implemented once the changes in industrial fuel utilisation are better understood/ developed.

5.4.3 Grey and blue hydrogen production

Hydrogen production is likely to be a well-regulated and controlled process (see Section 3), and therefore it will likely be possible for the UK Inventory to bypass more simplistic and limited approaches and jump straight to the use of improved approaches by the time that standalone grey and blue hydrogen production is happening at scale.

It is acknowledged that, for blue hydrogen production, the methodology may need to distinguish between carbon capture for permanent storage versus for utilisation. This will be part of the CCUS improvement project and is not considered further in this report. In alignment with IPCC good practice for carbon capture activities, carbon capture at blue hydrogen production facilities should follow a measured approach [35].

In deriving emission estimates from grey and blue hydrogen production, our working assumption is that all such plant in the UK will be large installations that are either standalone or units within a wider complex, all of which will be regulated under the EPR/IED and have a permit to operate with the environmental regulatory agency. In all cases it is expected that plant operators will report annual emissions (of all pollutants above reporting thresholds) to the pollution inventories, as well as participating in the UK ETS.

Based on current UK regulation, an installation that performs ‘production of hydrogen and synthesis gas by reforming or partial oxidation with a production capacity exceeding 25 tonnes per day’ qualifies as an installation under the GHG ETS Order (2020) and therefore is subject to ETS reporting [36].

Therefore, the project team anticipates that information on carbon dioxide emissions (and carbon dioxide sent to permanent storage via CCS plant) will become available to the inventory agency via the ETS data processing route common to all high-emitting sectors of the UK economy. Similarly, it is expected that reporting of other pollutants (e.g. other GHGs, NOx, NMVOC, particulate matter) will be delivered to the inventory agency via the PI and be pre-processed and gap-filled along with all other similar units/ sources.

The project team noted that to obtain annual emissions data via these routes specific to hydrogen production, may be problematic where the hydrogen unit is only one unit within a larger complex, and hence it may not be practicable to isolate the emissions specific to hydrogen unless additional, more detailed, emissions data were provided by the operator.

Furthermore, to derive UK-specific EFs (e.g. per hydrogen production technology or feedstock type) may also not be feasible unless installation-level annual hydrogen production data can be accessed by the inventory agency; such data are not routinely available via either the PI nor the ETS and the inventory agency may need to request supplementary data from operators and/or regulators. Obtaining hydrogen production data for these large installations will be necessary in order to embed the emissions estimates within the wider reported hydrogen production data in DUKES, and to help minimise the risk of gaps or double counts in the NAEI.

The project team anticipates that to develop a more detailed technical understanding of plant design, production capacity and combustion unit performance will be feasible through deep-dive research into the data analysis, environmental impact assessment and permit application process for the emerging hydrogen clusters as they move towards commissioning and operation. Analysis of these data may enable generation of initial EFs per unit type, prior to the annual emissions reporting routines becoming established to populate inventory estimates.

Model requirements

Per the earlier sectors, the project team envisages that the data processing needs will be accommodated partly within existing pre-processing NAEI models for UK ETS and PI datasets and partly via a new standalone hydrogen production model to pull together all of the reported activity and emissions data, to gap-fill for any non-reporting plant and to ensure that the UK inventory correctly reports emissions only from the emissive hydrogen production technologies and is aligned (where appropriate) with the UK ETS and PI emissions data.

5.4.4 Ammonia fugitive emissions

Emissions of ammonia have been cited as a concern by various stakeholders when discussing its use as a hydrogen carrier. Based on our stakeholder engagement and literature review, there is limited available information on the fugitive emissions impact of ammonia outside the traditional context of agricultural applications. It is therefore our suggestion that, should policy decisions indicate that there will be a role for ammonia as a hydrogen carrier or for use in shipping, that additional research is undertaken to assess the potential of fugitive emissions of ammonia.

In the absence of further research, it is assumed that AD could be taken from DESNZ Energy Statistics if ammonia becomes a category that the IEA recommends countries to report against. It is not possible at this stage to comment on the likely EFs of ammonia from its use as a hydrogen carrier.

6 Conclusions

This project has set out the inventory methods and data reporting systems that are likely to be required in the future to enable the UK NAEI to deliver emission estimates from sources across the hydrogen value chain.

Through research, stakeholder engagement, and detailed review of existing UK NAEI data reporting systems and inventory models, the project has proposed for each priority area:

- Suitable data sources, both for AD and EFs (see also Annex F).
- Mechanisms for data reporting into NAEI through existing or likely to be developed reporting requirements (e.g. environmental, and other reporting mandates).
- Suitable methods for reporting into the NAEI, including initial approaches (low tier,) and improved approaches (higher tier, increased granularity).
- NAEI model requirements, including viable incorporation into existing NAEI models, or needs for development of new models.

The proposed methods for reporting into the NAEI include initial and improved approaches. The initial approaches would predominantly draw on information from the DESNZ energy statistics team (i.e. hydrogen commodity balance tables) for AD and then apply EFs from literature sources to derive emission estimates. These initial approaches would be lower Tier (e.g. Tier 1). They would improve NAEI completeness, but as the methods may not accurately represent UK circumstances the emission estimates would be associated with high uncertainty or a low understanding of potential uncertainties.

The proposed improved approaches will typically draw upon data arising from new research (e.g. to derive country-specific or technology-specific EFs) and reporting mechanisms as they are established in the UK, such as installation-level activity and emissions data from mechanisms such as operator reporting under the ETS or the IED/PRTR. These higher-Tier methods are expected to deliver emission estimates that are more representative of UK emission sources and therefore are associated with lower uncertainty (or an improved understanding of uncertainties) than the simple Tier 1 methods. Their implementation is dependent on the development of new evidence and reporting systems; it may be several years before the UK evidence base is sufficiently developed to implement them within the UK inventory.

It has not been possible to assess uncertainty associated with these approaches due to limited available data. Based on the project team's professional judgement, from a qualitative perspective, we expect that the understanding of uncertainties is likely to be lower for hydrogen fugitive emissions and ammonia. We are more confident that, in due course, an estimate of uncertainty will be more feasible for industrial and power sector emissions.

In deciding the suitable approach to implement for each priority source, it will be important for DESNZ to assess the optimum approach to maximise efficiency of inventory improvement investment. There could be a risk that DESNZ invests in development of lower tier methods (with all of the associated downstream NAEI output development), only for these to be obsolete within a very short timeline once the higher-tier methodologies (more granular and likely more accurate) come within grasp due to the development of improved data reporting mechanisms. In this regard, DESNZ should ensure that any NAEI models are developed to be future proof, ensuring the model structure and calculation resolution will enable incorporation of more granular emissions sources, AD and EFs, as these are developed in the future.

In terms of suitable data sources and data sets, significant research is still needed in all priority areas to develop better understanding on the level of magnitude of emissions, to develop the needed datasets and develop suitable measurement techniques and protocols. To develop accurate estimates will warrant a significant investment in:

- Research to derive best AD estimates of hydrogen use per sector, per technology/ unit type.
- Research to conduct emissions tests across a representative range of fuel-technology combinations in order to develop EFs at a suitable level of detail and accuracy to apply to the AD.

The recommendations to DESNZ are to ensure engagement with relevant research bodies and other government institutions to ensure research funding is well coordinated and focused, as well as enhance communication and cross-collaboration between entities and deliver agreed/aligned useful outcomes. The international landscape review also found that there is limited additional information internationally, and that there will be benefit in the UK collaborating and maintaining dialogue with international agencies and bodies.

Likewise, for Inventory purposes, it will be paramount that DESNZ ensures regulation coverage across hydrogen value chain is complete, avoiding gaps and ensuring all regulatory reporting requirements are aligned and consider the NAEI dataset needs, with sufficient resolution and granularity.

It is also recommended that DESNZ enables monitoring and learning from first projects. In the initial phase of developing and testing new NAEI hydrogen reporting methods, a key information resource is expected to be data from the leading clusters/ projects that are first-movers, and all of the underlying environmental impact assessments, applications to operator (submitted to regulators as part of the permitting process under IED/EPR).

6.1 'Ideal' data reporting system and summary of gaps

The project found that whilst data sources and methods are different for each source category, there are common datasets and reporting systems required to support all hydrogen value chain source categories. If these reporting systems are well designed, resourced and implemented, the UK will have the evidence needed to report hydrogen value chain emissions in the NAEI and be able to track the impact of the hydrogen economy.

These 'ideal' reporting systems are discussed in Section 5.3 and summarised below, together with a gap analysis that helps identify the priority actions for the future.

Hydrogen commodity balance

The common data reporting systems and methods needed to support high quality reporting of hydrogen value chain emissions in the NAEI include the development of a complete and granular hydrogen commodity balance by DESNZ Energy Statistics. This dataset should provide, at a granular level, a suitable breakdown of hydrogen AD across the value chain that will be used for all source category reporting systems, enabling reporting of emissions from all priority areas.

It is in DESNZ' authority to develop this commodity balance and this be developed in the short term to comply with IEA requirements of hydrogen reporting by 2025. As this balance is yet to be developed, there is an opportunity for DESNZ to ensure the commodity balance will be of sufficient granularity and resolution to support NAEI reporting needs.

DESNZ Energy Statistics provided a draft hydrogen commodity balance which, alongside commentary on Inventory requirements, is available in Annex A.

UK ETS reporting

As discussed in Section 4.1 the UK ETS is a key data source for emissions for high-emitting combustion and industrial processes that are covered by this regulation.

The ideal data reporting system for hydrogen value chain will draw upon installation-specific data from ETS for hydrogen production emissions (grey or blue hydrogen), with measurements for carbon capture volumes (blue hydrogen production). Also, ideally the ETS should collect hydrogen consumption AD at large installations.

Hydrogen use AD from installations combusting hydrogen, which would support reporting of emissions from hydrogen combustion, will not be covered by ETS so other suitable AD collection mechanisms will need to be stablished.

Additional to UK ETS, installation-specific data from IED/PRTR reporting mechanisms (as discussed in Section 4) will also support the development of country specific UK EFs for hydrogen production and hydrogen use emissions in industrial installations.

Hydrogen combustion measurement and EFs

For atmospheric pollutant reporting from hydrogen use the ideal reporting system would rely on measured NOx data for all sites under the IED (reported to PI), and for those not reporting to PI or PRTR on consistent estimation methods and supported by EFs. Therefore, well developed country specific hydrogen combustion NOx EFs in all applications across the value chain would be needed, particularly for diffuse transportation and consumption activities (as these are not subject to IED/PRTR reporting).

Hydrogen fugitive emissions measurement and EFs

Hydrogen fugitive emissions at production sites would ideally be monitored and reported to the PI or estimated and reported to DAs environmental regulators by production facilities. Hydrogen fugitive emissions from transport via new hydrogen pipelines and from blending in the existing gas transmission and distribution system should be measured or estimated via a model (similar to the British Gas SLM) that has been calibrated with measurements. For other value chain stages developed country specific EFs would be required.

Ammonia fugitive EFs

Ammonia fugitive emissions from industrial installations covered by IED/PRTR are reported by industrial operators (when above threshold). To report fugitive emissions from ammonia across the entire value chain, significant research would be needed to develop suitable EFs. This is currently an underdeveloped area, but it is recognised that as the prominence of ammonia as a hydrogen carrier in the future economy is still uncertain, there may be other, higher priority areas of focus in the near-term.

6.2 Summary of suggestions for future research

Based on the outcomes from this report and the gaps identified to enable an ideal dataset for hydrogen value chain emissions reporting in the NAEI, there are a number of recommendations for DESNZ to consider:

1. DESNZ to ensure that collaboration between the NAEI inventory agency and the DESNZ Energy Statistics team is maintained as the hydrogen commodity balance tables and their associated data supply mechanisms (e.g. industry and fuel supplier surveys, annual operator returns to DESNZ) are developed over the coming years. As the hydrogen economy develops, the precise requirements of the national inventory will continue to evolve and become clearer. There is likely a high level of granularity required in the AD that are generated in order to populate a national energy balance. The DESNZ energy statistics team has yet develop a hydrogen commodity balance data gathering and reporting system (a draft hydrogen commodity balance, provided by DESNZ Energy Statistics, is available in Annex A). The study team notes that key features that are likely needed for the purposes of reporting the national inventory will include:

   a. A commodity balance that presents data at a similar level of resolution to the current natural gas commodity balance i.e. including reported annual consumption at a level of resolution that includes per transport mode, details of both energy industry consumption and use in fuel transformation.
   b. Resolution of annual hydrogen production data per technology and per feedstock.
   c. Information on transfers of hydrogen into / out of other commodity balance, for example where there may be transfers of hydrogen into gas blends/networks and where hydrogen is used within the production of ammonia or other hydrogen carriers, e.g. methanol.
2. DESNZ to work with government policy teams and regulators to ensure a comprehensive regulatory framework for hydrogen is implemented. Regulatory mandates should be implemented for operators to report to industry (Ofgem, NSTA) and environmental regulators (EA, SEPA, NRW, NIEA) on a regular basis. Likewise, industry operators should be mandated to provide data to Statistical agencies as required (e.g. through surveys).
3. DESNZ to work with UK ETS team, Hydrogen Regulatory Forum and industrial regulators, to ensure that requirements are set out for reporting of hydrogen AD, hydrogen fugitive emissions, GHGs and air quality pollutants through environmental and/or industrial regulation. As the regulatory framework is developed, and as a means to identify gaps, a map of institutional reporting requirements across the value chain could be developed, to enable collaboration and coordination of efforts to remove any gaps.
4. DESNZ and environmental regulators to work close with industrial clusters to influence and track how are they plan and track “first of a kind” projects. Use these projects to test proposed regulation. DESNZ to promote communication between regulators and project designers, developers, and operators to ensure common understanding of data measurement and reporting challenges, with the aim to implement suitable and well resolved data reporting systems, but also pragmatic and feasible.
5. DESNZ to coordinate with UK research bodies and other government institutions to ensure research funding bodies are optimised and enhance communication and cross-collaboration between entities to deliver agreed/aligned useful outcomes. DESNZ to ensure collaboration with international inventory agencies (e.g. US EPA) to ensure research work is coordinated.
6. DESNZ to engage with research agencies to coordinate further research in obtaining a reliable well-developed set of EFs for hydrogen combustion atmospheric pollutant and GHG emissions. Our current understanding is that certain value chain emission sources and technologies, such as domestic/commercial boilers, are more developed than others. More research will be needed, and it will be important to coordinate efforts with other peers internationally like US EPA, JRC and others.
7. DESNZ to follow up on outcomes from ongoing research (e.g. by NPL and others) to obtain a reliable well-developed set of hydrogen leakage estimates from across the full hydrogen value chain. It will be important to understand the science and measurement techniques suitable across the value chain, so that the data reporting requirements through regulation can be set out accordingly (e.g. where measurement is necessary and feasible, as opposed to indirect calculation or estimation methods)
8. DESNZ to continue work with industry (e.g. gas distribution network operators) to develop a measurement-enabled model for hydrogen leakage from pipelines. Research on leakage with hydrogen blending and methods to calculate this. Engage with transport operators to develop models for non-pipeline transport and storage.
9. DESNZ to work with environmental regulators and other government agencies, like the Department for Transport, to plan and develop research in the area of ammonia fugitive emissions. This area is significantly less developed than hydrogen emissions, and it will require a common decision on the research needs and priorities in the short term, which depend on the likelihood of ammonia becoming significant as a hydrogen carrier.

A. Annex: Draft hydrogen commodity balance

Table A.1: Draft hydrogen commodity balance (left column, provided by DESNZ Energy Statistics). Commentary on draft commodity balance (right column, developed by project team).

Hydrogen	Commentary
Production	The NAEI will also need supplementary data that presents the UK hydrogen production resolved according to technology and feedstock, as these impact (significantly) on the EFs per unit production.
Other sources	
Imports	
Exports	
Marine bunkers	
Stock change	
Transfers	The NAEI is likely to need data on hydrogen transferred to other gas blends, e.g. with natural gas supplies. Possibly also transfers in, e.g. from waste materials used to generate hydrogen
Total supply	
Statistical difference	
Total demand	
Transformation	The NAEI will likely also need information on the use of hydrogen in fuel transformation to other energy carriers such as ammonia or methanol
Electricity generation	
Major power producers	
Auto generators	
Heat generation	
Petroleum refineries	
Coke manufacture	
Blast furnaces	
Patent fuel manufacture	
Other	
Energy industry use	
Electricity generation	
Oil and gas extraction	
Petroleum refineries	
Coal extraction	
Coke manufacture	
Blast furnaces	
Patent fuel manufacture	
Pumped storage	
Other	
Losses	
Final consumption	
Industry	
Unclassified	

Hydrogen	Commentary
Iron and steel	
Non-ferrous metals	
Mineral products	
Chemicals	
Mechanical engineering etc	
Electrical engineering etc	
Vehicles	
Food, beverages etc	
Textiles, leather etc	
Paper, printing etc	
Other industries	
Construction	
Transport	
Air	
Rail	
Road	The NAEI would Ideally also obtain a greater level of resolution to indicate hydrogen use per road transport vehicle type (e.g. passenger cars, LDVs, HGVs, other)
National navigation	
Pipelines	
Other	
Domestic	
Public administration	
Commercial	
Agriculture	
Miscellaneous	
Non energy use	

Notes were not able to be reviewed during this project as these were not shared by DESNZ Energy Statistics].

B. Annex: Summary of findings from other countries review

Table B.2: Summary of findings from other countries review

Country	Findings
United States	**Relevant policies and programmes** The NC report [37] outlined priorities and actions taken to drive the development of the hydrogen economy. Relevant policies and programmes include the launching of the Regional Clean Hydrogen Hubs, Clean Hydrogen Electrolysis Programme, and the Clean Hydrogen Manufacturing and Recycling Initiatives, which are all part of the Bipartisan Infrastructure Law. These programmes support the research, development, demonstration, and deployment of hydrogen production and consist of a network of producers, potential off-takers and supporting infrastructure. The Alternative Fuel Corridors Programme [38], implemented in 2016, published corridor information, technical guidance on fuel cell vehicles and hydrogen fuel station network development. The Basic Energy Sciences Research Programme [39], in operation since 2010, produced chemical and materials science research, and LCA tool for low-emission hydrogen production, such as the GREET hydrogen model. The IEA report noted that the Department of Environment has allocated more than 10 million USD funding towards researching hydrogen as an indirect GHG and ppb-level hydrogen sensors development. There have been several hydrogen fugitive emissions monitoring projects underway, such as the hydrogen emissions measurement study projects, led by Aerodyne Research and the Environmental Defence Fund, to develop hydrogen sensors, though the projects have not yet reached commercial viability. **Inventory** The only mention of hydrogen within the inventory related to ammonia and other existing chemical industry processes. The only mention of hydrogen within the CRF table was in the definition of still gas; this indicated that some fugitive emissions of hydrogen were theoretically captured within reporting, however it was treated as a petroleum product rather than reported as a fugitive emission of hydrogen. The search for fuel cells and alternative fuels showed that the USA reported vehicle miles travelled (VMT) from hydrogen fuel cell vehicles. AD were taken from vehicle sales data. EFs of fuel types were noted to come from the GREET model. The AFLEET tool included data on hydrogen fuel cells, though it did not mention N_2O or H_2, and assumes zero NOx emissions for fuel cells [40]. The National Emissions Inventory Data Retrieval Tool [41] has been reviewed, though the tool had limited information relevant to NOx and ammonia emissions methods.
Australia	**Relevant policies and programmes** The IEA report noted that Australia produces half of the hydrogen trade projects by export volume. With a focus on global market penetration, the government has initiated the Regional Hydrogen Hubs Programme [42], which has been supporting the development of five regions as of 2023 [43], along with funds that target hydrogen production and use infrastructure development, such as the Advancing Hydrogen Fund, the CCUS Development Fund, and the Driving the Nation Fund. The government developed a Hydrogen Guarantee of Origin scheme [7] to track emissions, along with the technology type and energy source used in domestic hydrogen production. The scheme provides an online Emissions Accounting Approach Calculator to enable users to estimate emissions intensity of hydrogen. The scheme aligns with international approaches, using the IPHE methodology as the basis of the scheme framework [5,44]. A public database of hydrogen industry development is currently managed by the Commonwealth Scientific and Industrial Research Organisation (CSIRO) on the HyResource platform [45]. The government is also working with the Australian Renewable Energy Agency (ARENA) and Clean Energy Finance Corporation (CEFC) to provide funding towards RD&D projects. For instance, the Australian Hydrogen Centre [46] produced feasibility studies on the decarbonisation of the existing natural gas distribution networks, such as the Hydrogen Blending Studies 2023 [47], which examined

	the blend ratio control systems and the measurement of gas delivered via zonal heating value methodology. **Inventory** The mention of hydrogen within the reports mostly related to ammonia production processes. However, the report noted that hydrogen production via electrolysis using renewable electricity was expected to be implemented on a broad scale, therefore, planned improvements would establish a process to ensure the reporting identifies and tracks the implementation of ammonia production from renewable sources. No further details were provided. Within the CRF table, under category 2.B.10.a. hydrogen production was stated as IE (Included elsewhere) and was integrated with the ammonia and other petrochemicals production reporting. Regarding ammonia production, the report noted that only CO_2 emissions from the use of natural gas as a feedstock were reported in the industrial processes and product use sector. Seven ammonia production plants were reported in Australia, and the companies provided natural gas consumption and CO_2 recovery data for the inventory. The National Pollutant Inventory [48] has been reviewed, though there was very limited information available on NOx and ammonia emissions calculation methods.
Netherlands	The government has launched a National Hydrogen Programme accompanied with various subsidy schemes and grants programmes, such as the Sustainable energy production subsidy scheme (SDE++) incentive scheme and National Growth Fund for low-carbon production technologies [49]. Key projects include the NorthH2 Project [50]. As one of the largest European green hydrogen projects, it targets to produce hydrogen via offshore wind of 4 GW by 2030 to supply 300kt of hydrogen across Northwest Europe. The project has currently completed its feasibility phase. Netherlands has also defined five regional industrial clusters, which includes the twelve largest emitting companies. The clusters submitted climate energy strategies in 2021 and was incorporated into the Programme on Energy and Climate Infrastructure. Regarding hydrogen distribution, HyWay27 [51], a collaborative study between the Dutch Ministry of Economic Affairs and Climate Policy, and network operators Gasunie and TenneT, was published in 2021. This report explored the potential of the existing national gas grid for hydrogen transportation. While the report noted the concerns of leakage, no specific information related to measuring emissions was provided. **Inventory** The mention of hydrogen within the inventory related to ammonia and other existing chemical industry processes. The NIR stated that there is a Shell Gasification and Hydrogen Production (SGHP) unit that has been operating in one refinery since 1998. Process emissions/ fugitive CO_2 emissions of the plant have been reported in category 1B2a4 since 2002. Regarding transport emissions, the inventory's supplementary submission, *Methods for calculating the emissions of transport in NL1,* provided implied EFs for road traffic of each vehicle category. EFs were indicated as 0 or blank for all vehicle types that use hydrogen as fuel. The NIR noted that EFs for alternative fuels were derived from Ligterink et al. [52], though hydrogen was not mentioned in this literature source. The NIR noted planned improvements of applying the 2019 refinements for hydrogen production. The Informative Inventory Report [53] has been reviewed, though the report had limited information relevant to NOx and ammonia emissions calculation methods.
Japan	Japan has updated its Hydrogen Strategy in 2023 to reaffirm its goal of demonstrating 30% co-firing of hydrogen in large gas turbines and 50% ammonia co-firing in coal power plants by 2030 [4]. Numerous demonstration projects have already been announced or commenced by Japanese heavy industry manufacturers, with some expected to be commercial before 2030. For instance, the Kawasaki Heavy Industries (KHI) has announced the world's first 100% hydrogen-fuelled gas turbine operation with dry low NOx combustion technology in 2023 [10]. The IHI Corp has demonstrated the application of 100% liquid ammonia combustion in a 2 MW gas turbine in 2022, efforts are underway to decrease NOx levels, with the aim of achieving practical application by 2025 [9]. Regarding hydrogen transportation, the IEA report noted that ammonia is expected to be the main carrier for low-emission hydrogen transport on major international trade routes. Japan is a significant hydrogen importer, with planned or completed trade pilot projects for ammonia and LOHC with Saudi Arabia, Brunei, and Australia. The Hydrogen Energy Supply Chain (HESC) project [54] plans to reach

	trade volumes of 225,000t annually, and the first cargo of 75t liquified hydrogen was delivered from Victoria to Japan in 2022. The NC offered a commentary on the promotion of the hydrogen economy, with the goal to achieve the commercial production of hydrogen by 2030 [55]. One of the cross-cutting measures is the introduction of J-Credit Scheme [56], a carbon offsetting scheme administered by the government. The scheme includes carbon calculation methodologies for fuel switch (from fossil fuel or grid power to blue hydrogen or ammonia fuel) and hydrogen fuel cell vehicles. **Inventory** The mention of hydrogen within the inventory related to existing chemical industry processes. The quantity of hydrogen production was reported under the CRF table of Sector Background Data for Industrial Processes and Product Use. The data on CO_2 emissions from the production of hydrogen for CO_2 was reported with CO_2 recovery being 'NE' (not estimated). AD of hydrogen production was reported by member companies of the Japan Industrial and Medical Gases Association. The NIR listed the EFs for hydrogen production since 1990. The EFs per production was calculated by dividing the aggregated CO_2 emissions with the aggregated production data provided by the industrial gas producers. Databases and publications from the National Institute for Environmental Studies [57] have been reviewed, though there was very limited information available on NOx and ammonia emissions calculation methods.
Germany	Hydrogen projects are often funded and initiated by the Federal Ministry of Education and Research (BMBF) [58]. For instance, numerous industry-led hydrogen projects have been launched since 2021. With more than 200 science and industry partners, key lead projects include H2Giga on hydrogen production and scaling up electrolysers, H2Mare on offshore hydrogen production, and TransHyDE on transport solutions. The projects are deemed to complete in 2025. Germany's H2Global [59] is one of the most developed hydrogen auction initiatives across the world. The auction with a budget of 900 million EUR was launched in 2022, and deliveries are planned to initiate in 2024. Other countries, such as the Netherlands, also intend to use this initiative for hydrogen imports auctioning. Regarding hydrogen transport, a draft proposal of a superregional hydrogen transport network, with 60% of repurposed natural gas pipelines, was submitted by transmission system operators in 2023 [60]. At an international scale, a feasibility study was completed in 2023 to assess large-scale hydrogen transport from Norway to Germany [61]. While the feasibility report did not cover fugitive emissions, a joint task force had been set up between the two countries for follow-up discussions. **Inventory** The Centre for Solar Energy and Hydrogen Research Baden-Württemberg is responsible for processing renewable energies for the inventory energy balance and has coordinated various research projects on hydrogen production, use, and fuel cells. Hydrogen was not mentioned in the CRF table, and the only mention within the inventory related to chemical industry processes. EFs of produced gases with high calorific values and with large hydrogen fractions were calculated from emissions trading data (EU ETS) for the chemical industry. Ammonia has been produced in four plants in Germany as of 2014. Plant-specific data was submitted to the Industrieverband Agrar agrochemical industry association, which was then aggregated by the Federal Environmental Agency for reporting. The Informative Inventory Report [62] has been reviewed, and the report noted that the default CORINAIR Guidebooks emission factors had been used for estimating NH_3 emission from ammonia production. No further information was given in the report.

C. Annex: Hydrogen value chain regulation mapping

Table C.1: Hydrogen value chain regulation map

Value chain step	Technology/ method/ scale	Existing applicable regulation (note some regs only apply subject to size/scale/emissions thresholds)	Proposed regulation, changes and/or new regulation	Other reporting mechanisms or obligations	Reference documents for proposed regulation
Production	Electrolysis	IED (BAT), EPRs, PRTR	Will be covered by IED. IED likely to be modified to have separate category for hydrogen production via hydrolysis with a defined threshold, small installations might not be covered. The Hydrogen Regulators Forum is working on producing a guidance document (precursor to BAT) for electrolysis	Those projects seeking funding through the low carbon business model will have to meet the UK Low Carbon Hydrogen Standard (LCHS), which requires to have a plan to reduce hydrogen fugitive emissions	• Low Carbon Hydrogen Business Model: government response to consultation. • Comments on IED are from SEPA stakeholder consultation meeting. • Hydrogen Regulator´s Forum information from EA stakeholder consultation meeting
	Blue (SMR/ATR + CC)	ETS, IED (BAT), EPRs, PRTR	ETS already includes reporting rules for grey and blue hydrogen and CC. Environmental regulators through the Hydrogen Regulators Forum have developed guidance for blue hydrogen with CC (to be further developed into BAT when more evidence exists) which includes recommendation to monitor hydrogen fugitive emissions	Those projects seeking funding through the low carbon business model will have to meet the UK Low Carbon Hydrogen Standard (LCHS), which requires to have a plan to reduce hydrogen fugitive emissions	• Proposals for hydrogen production and industrial carbon capture regulations - consultation. • Low Carbon Hydrogen Business Model: government response to consultation. • ETS coverage from stakeholder meeting with EA-ETS
	Offshore production	Unknown	OPRED and or the devolved administrations, DAs decide. In Scotland the manufacture of gases is devolved to Scottish Ministers. Unclear how it will work with other devolved administrations	-	• OPRED stakeholder meeting
Transportation	Pipeline - onshore transmission	No specific environmental regulation. Other non-economic regulation: Gas Act 1986 and Planning Act 2008, Gas safety management regs GSMR 1996	OFGEM likely to become the regulator (economic) in a similar model as currently applied to natural gas transmission. Not officially announced in Gov documents yet	Gov plans to design hydrogen transport business model by 2025	• OFGEM call indicated they are likely to be regulators. • Hydrogen Transport and Storage - response to consultation - this document states government still deciding what changes are needed to regulation and that in the interim Gov is working with Ofgem and industry to enable early projects to operate within existing regulatory regimes.
	Pipeline - onshore distribution	No specific environmental regulation. Other non-economic regulation: Gas Act 1986 and Planning Act 2008, Gas safety management regs GSMR 1997	OFGEM likely to become the regulator (economic) in a similar model as currently applied to natural gas transmission. Not officially announced in Gov documents yet	Gov plans to design hydrogen transport business model by 2025	• OFGEM stakeholder meeting indicated they are likely to be regulators. • Hydrogen Transport and Storage - response to consultation - this document states government still deciding what changes are needed to regulation and that in the interim Gov is working with Ofgem and industry to enable early projects to operate within existing regulatory regimes. • Hydrogen blending into the GB Gas Distribution Networks - Consultation
	Container - tube trailer	No specific environmental regulation. Other non-economic regulation: Gas Act 1986. Agreement Concerning the International Carriage of Dangerous Goods by Road (ADR), Carriage of Dangerous Goods and Use of Transportable Pressure Equipment Regulations 2009 (CDG)	Nothing proposed for environmental regulation	Government will work with DfT and HSE to review existing safety standards and regulations, possible amendments to ADR.	• Hydrogen Transport and Storage - response to consultation
	Ship - offshore	Unknown	Not OPRED, Unknown	-	• OPRED stakeholder meeting

Value chain step	Technology/ method/ scale	Existing applicable regulation (note some regs only apply subject to size/scale/emissions thresholds)	Proposed regulation, changes and/or new regulation	Other reporting mechanisms or obligations	Reference documents for proposed regulation
	Pipeline - offshore	No specific environmental regulation. Hydrogen is currently not defined as gas under the Energy Act 2008, meaning that offshore hydrogen injection and storage is not yet covered by any regulation	NSTA is proposed to be the relevant consenting authority, and OPRED to be the environmental regulator by bringing hydrogen pipelines and storage in scope of the 2020 Offshore EIA Regulations and the Habitats Regulations.	-	• Offshore Hydrogen Regulation - response to consultation • Hydrogen Transport and Storage - response to consultation. • Call with OPRED - statutory instrument enabled with OPRED as reg for offshore hydrogen projects, pipelines and storage
Storage	Geological storage (salt cavern)	Unknown	A Future Systems Operator (FSO) to be stablished and take a strategic planner role (UK gov has this role until then). No further decisions on who will be economic or environmental regulator	Government plans to develop a dedicated hydrogen storage business model focused on large-scale geological storage. This likely to be delivered by a private law contract and will require a counterparty to manage these contracts. Who the counterparty will be not decided yet by Government	• Hydrogen Transport and Storage - response to consultation
	Above ground (liquified or gaseous)	No specific environmental regulation. Other non-economic regulation: COMAH (tbc)	A Future Systems Operator (FSO) to be stablished and take a strategic planner role (UK gov has this role until then). No further decisions on who will be economic or environmental regulator	-	• Hydrogen Transport and Storage - response to consultation
	Chemical storage (ammonia, methanol, metal halides)	Unknown	A Future Systems Operator (FSO) to be stablished and take a strategic planner role (UK gov has this role until then). No further decisions on who will be economic or environmental regulator	Government believes it requires more technological development before it can receive government support	• Hydrogen Transport and Storage - response to consultation
	Offshore storage	Unknown	NSTA is proposed to be the relevant consenting authority, and OPRED to be the environmental regulator by bringing hydrogen pipelines and storage in scope of the 2020 Offshore EIA Regulations and the Habitats Regulations	-	• Offshore Hydrogen Regulation - response to consultation • Hydrogen Transport and Storage - response to consultation • Call with OPRED - statutory instrument enabled with OPRED as reg for offshore hydrogen projects, pipelines and storage
Use	Gas turbines	ETS, IED (BAT), MCPD, EPRs, PRTR	Will be covered by IED (>50MW), MCP (<50MW), Environmental permitting and possibly PRTR (depending on industry and thresholds)	-	-
	Domestic/Commercial	Ecodesign standards for <1MW. MCP for > 1MW	Ecodesign standards for <1MW, for >1MW and up to 50MW is MCP directive	-	• Defra stakeholder meeting
	Process - Industry	ETS, IED (BAT), MCPD, EPRs, PRTR	Will be covered by IED (>50MW), MCP (<50MW), Environmental permitting and possibly PRTR (depending on industry and thresholds)	-	-
	Fuel cell	Vehicle air pollutant emissions standards	No specific environmental reporting regulation	-	-
	Internal combustion	Vehicle air pollutant emissions standards	No specific environmental reporting regulation	-	-

This table has been generated for the specific purposes of this project and context (NAEI emissions reporting requirements) – it should not be utilised out of context as it will not be a comprehensive summary of all regulation related to the hydrogen economy. Many elements of regulation are still nascent and evolving and therefore this information is subject to change.

D. Annex: Research projects on GHG and AQP emissions of hydrogen economy

The projects and resources identified are outlined in the tables below.

Table D.3: Projects and resources on GHG and AQP emissions of hydrogen economy

Project/ resource	Lead	Sector/ application	Relevance	Timeframe, if known	Link
DECARB (Euramet project)	Various (inc. NPL WP lead for leak)	Various	Covering 'the priority challenges within flow metering, gas composition, physical properties and safety (including monitoring of gas leaks)'. NPL leading work package on leaks/ emissions including assessment of hydrogen leak detection technologies	May 2024	Link
GOTT (Government Office of Technology Transfer) hydrogen measurements	NPL	Hydrogen leak measurement capabilities	Covering three outputs: develop testing capabilities (controlled release), leak detection and quantification of individual hydrogen leaks, site level continuous monitoring (done for natural gas, to be adapted for hydrogen)	March 2024	NA
Defra & EA – hydrogen leak detection techniques	NPL	Various	Review of commercially available leak detection techniques, to support the EA's activity of developing further guidance	February/ March 2024	NA
MefHySto	Various (inc. NPL)	Underground storage	Metrological issues of large-scale hydrogen underground gas storage	August 2023	Link
Multi Gas Detection	National Gas Transmission	Pipeline transport	Testing a single gas sensor to simultaneously detect a mix of hydrogen and methane	March 2024	Link
Digital Platform for Leakage Analytics	Cadent	Gas distribution	Investigating potential to replace shrinkage and leakage model with real-world measurements. This is aimed at the existing natural gas distribution system, but our understanding is that they will be considering what it would require to extend to cover hydrogen	February 2026	Link (discovery) Link (alpha)
Leakage Management in the Energy System Transition	SGN	Gas distribution	'Provide recommendations on the requirements for hydrogen leakage modelling and management.' Considers 100% hydrogen.	Complete (February 2023)	Link
Fugitive hydrogen emissions in a future hydrogen economy	Frazer-Nash Consultancy	Cross value chain	Quantified leakage potential in a future energy system	Complete (April 2022)	Link
Hydrogen emissions from a hydrogen economy and their potential global warming impact	Clean Hydrogen Joint Undertaking (JRC)	Cross value chain	Potential hydrogen emissions from a hydrogen economy and their indirect GHG, includes hydrogen fugitive emissions estimates	Complete (April 2022)	Link
COSH-AIR (University College London-led elements)	University College London	Cross value chain	Modelling hydrogen leakage under different scenarios	Initial results expected early 2024	Link
UK Low Carbon Hydrogen Standard	DESNZ	Production	Requires participants to develop a monitoring plan for hydrogen leakage. Approaches may include direct monitoring of hydrogen streams (for example in vent ducts), or mass balance approaches to track overall flows of hydrogen.	Published (version 2, April 2023) but with potential for review	Link
JEP22 AI04 Environmental Aspects of Emissions from Firing Hydrogen in Combined Cycle Gas Turbines	Joint Environmental Programme (JEP)	End use	Potential future emissions by large combustion plants	Published, June 2023	NA

E. Annex: Detailed NAEI Methods

Note that more detailed NAEI methodologies have only been provided for subsections of the value chain, where the method is more complex and/or more likely to be transferrable to hydrogen.

E.1 Natural gas transportation and storage

E.1.1 Gas combustion at compressor stations

Many of the larger compressor stations across the UK gas network are permitted by the environmental regulatory agencies and are required to report annual emission estimates under IED/PRTR; in practice the emissions data reported via the pollution inventories of the regulatory agencies is highly incomplete as many sites fall well below the reporting thresholds (e.g. for carbon dioxide, methane, oxides of nitrogen). The emissions from gas combustion are therefore estimated using natural gas consumption AD within DUKES and emissions factors (UK-specific for carbon content based on gas compositional analysis – *see below* – and many defaults for other gases).

National Grid provides supplementary data on methane emissions from gas slippage at turbines (see below) direct to the inventory agency for use in NAEI methodologies.

E.1.2 Venting and fugitive emissions on the transmission and distribution network

The UK inventory includes estimates of methane, carbon dioxide and NMVOC emissions from natural gas leakage from the downstream gas supply network, including releases from: high pressure transmission network; distribution network; gas leakage at the point of use. Annual AD and gas compositional analysis are provided by National Grid, companies that operate the Gas Distribution Networks in Great Britain (Cadent, SGN, NGN, WWU), and gas suppliers in Northern Ireland.

The GHGI methodology used to estimate methane leakage from the natural gas transmission and distribution system is described within the National Inventory Report, Method Statement #19 (page 223 of the 2023 submission) and is summarised below.

E.1.2.1 Gas Leakage AD

National Grid: provide annualised estimates of methane due to sources including venting and gas leakage from the high-pressure NTS across all emission sources, including:

- Fugitive emission surveys at gas terminals, compressor stations.

- Fugitive emissions from Above Ground Installations (Marcogaz EF methodology).
- Fugitive emissions from pipelines (Marcogaz EF methodology).
- Gas venting from compressor stations, gas terminals, pipelines, pig traps, reduction and regulation stations, measurement stations, valve stations.
- Incomplete combustion of natural gas at compressor station turbines.
- [Historically – *now all closed* – from natural gas storage sites].

Cadent, NGN, SGN, WWU: all GDN operators use the UK industry Shrinkage and Leakage Model (SLM) to generate annual gas leakage estimates from sources across the distribution networks including from:

- Low pressure pipeline network leakage.
- Medium pressure pipeline network leakage.
- Above Ground Installation Leakage.
- Above Ground Installation working losses.
- Interference (includes theft, 'incidents').

E.1.2.2 Gas compositional analysis data

To enable the calculation of individual pollutants to be determined, each of the GDN operators also provides an annualised weighted average gas composition of the natural gas supplied per LDZ, as well as the annual gas throughout per LDZ to enable the inventory agency to calculate a UK-wide weighted average gas composition. The gas composition data provides the molar percentage share of the gas delivered, including nitrogen, carbon dioxide, methane, ethane, propane, i-butane, n-butane, neo-pentane, i-pentane, n-pentane and hexanes+.

Any future hydrogen – natural gas blend supplied through a UK pipeline network will need a mechanism by which the UK weighted average gas composition can be calculated on an annual basis. The project noted that this system will also need to be able to report on the composition of the gas that is from fossil natural gas and from biogas, in order to enable an accurate estimate of fossil CO_2 emissions to be derived for the inventory.

Gas composition analysis data from hydrogen – natural gas blends will also likely be needed to enable modelling of gas blend leakage rates. As described in section 3.3.2.1, the outcomes from recent research projects indicate that gas leakage rates are dependent on many factors including gas physical properties (density, viscosity), gas flow regime (laminar, turbulent) and pipe conditions (pressure, leak size, etc.). Therefore, any potential hydrogen-natural gas blend leakage model is likely to require average gas composition data an input.

E.1.3 Emissions from gas storage sites

Across the UK gas transmission system there were (*historically – now all closed*) several above ground onshore gas storage sites, which were permitted and subject to annual PI reporting to environmental regulators. The reported emissions data were supplemented by direct reporting by

National Grid to the inventory agency in order to generate complete estimates of methane and NMVOC emissions. These data are reported directly within the UK inventory.

There is one operational gas storage site offshore (Rough gas storage) and a number of depleted gas fields used to store natural gas adjacent to UK gas terminals and onshore production sites, predominantly in the east of England. The offshore installation is regulated by the upstream oil and gas regulator, OPRED, with annual emissions (per source, with separate emissions reported for: venting, flaring, fugitives, fuel combustion) reported within the EEMS. The onshore gas storage sites fall under Environment Agency regulation and report to the PI, subject to emissions being above the reporting thresholds. Operator-reported data within EEMS and the PI are gap-filled and used directly within the UK inventory.

The reporting of any emissions from hydrogen storage facilities will be dependent on the regulatory landscape for the storage sector, which at the time of writing this report is undecided.

E.1.4 Gas leakage at point of use

The UK GHGI also includes a bespoke UK method to estimate the release of methane from natural gas at the point of use, i.e. downstream of gas meters within the combustion units across end user sectors. This method is described in detail within the NIR (page 226 of the 2023 submission); it broadly comprises emission estimates from natural gas use within the residential and commercial sectors, using data from Energy Consumption in the UK (BEIS, 2022) [63] to estimate gas use across different types of appliances (e.g. cookers, boilers, space heaters) and then applies a series of assumptions (e.g. appliance operational cycles) to estimate the gas slippage pre-ignition per appliance type gas use.

F. Annex: Indicative data map for inventory methods

These indicative data maps for inventory methods are based on the approaches described in section 5.4. Please refer to section 5.4 for further context and commentary on these approaches. The tables below are intended for reference only.

F.1 Hydrogen Fugitive Emissions

Table F.1:Indicative initial approach, hydrogen fugitive emissions

		Activity Data				**Emission Factors**			**Model requirements**
Value Chain Step	**Sub-step / application**	**Activity**	**Units**	**Proposed data source**	**Cross-check / additional source**	**EF**	**Units**	**Proposed data source**	**Model requirements**
Production	**Electrolysis**	Hydrogen produced	mass or volume per year	DESNZ Energy Statistics	Operator data; innovation project production figures	Hydrogen fugitive emission rates	% by volume or mass	Frazer-Nash report fugitive assumptions	Likely new model required, though could be simple (summarised activity data x fugitive rate).
	SMR/ATR	Hydrogen produced	mass or volume per year	DESNZ Energy Statistics	UK ETS; operator data; innovation project production figures	Hydrogen fugitive emission rates	% by volume or mass		
	SMR/ATR+CC	Hydrogen produced	mass or volume per year	DESNZ Energy Statistics	UK ETS; operator data; innovation project production figures	Hydrogen fugitive emission rates	% by volume or mass		
Transportation	**Pipeline – transmission**	Hydrogen transported	mass or volume per year	DESNZ Energy Statistics	Ofgem; NSTA, OPRED, Gas Network operators	Hydrogen fugitive emission rates	% by volume or mass	Frazer-Nash report fugitive assumptions	Likely new model required or may require updates to existing fugitive model for natural gas transportation for hydrogen blending.
	Pipeline – distribution	Hydrogen transported	mass or volume per year	DESNZ Energy Statistics	Ofgem; NSTA, OPRED, Gas Network operators	Hydrogen fugitive emission rates	% by volume or mass		
	Container	Hydrogen transported	mass or volume per year	DESNZ Energy Statistics	Ofgem; NSTA, OPRED, Gas Network operators	Hydrogen fugitive emission rates	% by volume or mass		
Storage	**Salt Cavern**	Hydrogen stored	mass or volume per year	DESNZ Energy Statistics	Data from operators or regulators	Hydrogen fugitive emission rates	% by volume or mass	Frazer-Nash report fugitive assumptions	Likely new model required, though could be simple (summarised activity data x fugitive rate).

		Activity Data				Emission Factors			Model requirements
	Above ground	Hydrogen stored	mass or volume per year	DESNZ Energy Statistics	Data from operators or regulators	Hydrogen fugitive emission rates	% by volume or mass		
Use	**Gas turbines**	Hydrogen used	mass or volume per year	DESNZ Energy Statistics	Data from operators or regulators	Hydrogen fugitive emission rates	% by volume or mass	Frazer-Nash report fugitive assumptions	Likely new model required, though could be simple (summarised activity data x fugitive rate).
	Domestic / Commercial	Hydrogen used	mass or volume per year	DESNZ Energy Statistics	Data from researchers, trade associations, consumers	Hydrogen fugitive emission rates	% by volume or mass		
	Process	Hydrogen used	mass or volume per year	DESNZ Energy Statistics	Data from operators or regulators	Hydrogen fugitive emission rates	% by volume or mass		
	Fuel cell	Hydrogen used	mass or volume per year	DESNZ Energy Statistics	Data from researchers, trade associations, consumers	Hydrogen fugitive emission rates	% by volume or mass		
	Internal combustion	Hydrogen used	mass or volume per year	DESNZ Energy Statistics	Data from researchers, trade associations, consumers	Hydrogen fugitive emission rates	% by volume or mass		

Table F.2: Indicative improved approach, hydrogen fugitive emissions

		Activity Data				Emission Factors			Model requirements
Value Chain Step	**Sub-step / application**	**Activity**	**Units**	**Proposed data source**	**Cross-check / additional source**	**EF**	**Units**	**Proposed data source**	**Model requirements**
Production	**Electrolysis**	Hydrogen produced	mass or volume per year	DESNZ Energy Statistics	Operator data; innovation project production figures	Hydrogen fugitive emission rates	% by volume or mass	Measurements or calculated fugitive rates to derive either country-specific or facility-specific representative EFs, e.g. via DESNZ Innovation	Higher-tier methods. Designed to conduct calculations at an appropriate level of resolution, dependent on the AD and EFs available, e.g. per technology and feedstock, per sub-source. May need to account for facility-level emissions data.
	SMR/ATR	Hydrogen produced	mass or volume per year	DESNZ Energy Statistics	UK ETS; operator data; innovation project production figures	Hydrogen fugitive emission rates	% by volume or mass		
	SMR/ATR+CC	Hydrogen produced	mass or volume per year	DESNZ Energy Statistics	UK ETS; operator data; innovation project production figures	Hydrogen fugitive emission rates	% by volume or mass		

		Activity Data				Emission Factors			Model requirements
								projects (as required under LCH standard)	
Transportation	**Pipeline - transmission**	Hydrogen transported	mass or volume per year	DESNZ Energy Statistics	Ofgem; NSTA, OPRED, Gas Network operators	Hydrogen fugitive emission rates	% by volume or mass	UK or other specific research to derive representative EFs per sub-source	Higher-tier methods. Designed to conduct calculations at an appropriate level of resolution, dependent on the AD and EFs available, e.g. per source type across the delivery network, similar to the natural gas SLM. May need to account for facility-level emissions data, e.g. where installations are permitted under IED.
	Pipeline - distribution	Hydrogen transported	mass or volume per year	DESNZ Energy Statistics	Ofgem; NSTA, OPRED, Gas Network operators	Hydrogen fugitive emission rates	% by volume or mass	UK or other specific research to derive representative EFs per sub-source	
	Container	Hydrogen transported	mass or volume per year	DESNZ Energy Statistics	Ofgem; NSTA, OPRED, Gas Network operators	Hydrogen fugitive emission rates	% by volume or mass	UK or other specific research to derive representative EFs per sub-source	
Storage	**Salt Cavern**	Hydrogen stored	mass or volume per year	DESNZ Energy Statistics	Data from operators or regulators	Hydrogen fugitive emission rates	% by volume or mass	UK or other specific research to derive representative EFs per sub-source	Higher-tier methods. Designed to conduct calculations at an appropriate level of resolution, dependent on the AD and EFs available, e.g. per storage type across the transport and delivery network, including interim storage and point of delivery storage. May need to account for facility-level emissions data, e.g. where installations are permitted under IED.
	Above Ground	Hydrogen stored	mass or volume per year	DESNZ Energy Statistics	Data from operators or regulators	Hydrogen fugitive emission rates	% by volume or mass	UK or other specific research to derive representative EFs per sub-source	
Use	**Gas turbines**	Hydrogen used	mass or volume per year	DESNZ Energy Statistics	Data from operators or regulators	Hydrogen fugitive emission rates	% by volume or mass	UK or other specific research to derive representative	Higher-tier methods. Designed to conduct calculations at an appropriate level of resolution, dependent on the AD and EFs

		Activity Data				Emission Factors			Model requirements
								EFs per sub-source	available, e.g. per sector and sub-source. For gas turbines and industrial facilities, the method is likely to need to account for facility-level emissions data, e.g. where installations are permitted under IED.
	Domestic/Commercial	Hydrogen used	mass or volume per year	DESNZ Energy Statistics	Data from researchers, trade associations, consumers	Hydrogen fugitive emission rates	% by volume or mass	UK or other specific research to derive representative EFs per sub-source	
	Process	Hydrogen used	mass or volume per year	DESNZ Energy Statistics	Data from operators or regulators	Hydrogen fugitive emission rates	% by volume or mass	UK or other specific research to derive representative EFs per sub-source	
	Fuel cell	Hydrogen used	mass or volume per year	DESNZ Energy Statistics	Data from researchers, trade associations, consumers	Hydrogen fugitive emission rates	% by volume or mass	UK or other specific research to derive representative EFs per sub-source	
	Internal combustion	Hydrogen used	mass or volume per year	DESNZ Energy Statistics	Data from researchers, trade associations, consumers	Hydrogen fugitive emission rates	% by volume or mass	UK or other specific research to derive representative EFs per sub-source	

Table F.3: Indicative additional improved approach, hydrogen fugitive emissions

		Activity Data				Emission Factors			Model requirements
Value Chain Step	**Sub-step / application**	**Activity**	**Units**	**Proposed data source**	**Cross-check / additional source**	**EF**	**Units**	**Proposed data source**	
Production	**Electrolysis**	Hydrogen produced	mass or volume per year	Operator data per facility reported to regulators	DESNZ Energy Statistics	Hydrogen fugitive emissions	mass or volume per year	Operator data per facility e.g. reported to regulators (EA, SEPA, NRW,	Tier 3, aggregating all facility-level emissions data; the AD collected here are for info, to enable QC against DUKES / other data.

		Activity Data				Emission Factors			Model requirements
Value Chain Step	**Sub-step / application**	**Activity**	**Units**	**Proposed data source**	**Cross-check / additional source**	**EF**	**Units**	**Proposed data source**	
	SMR/ATR	Hydrogen produced	mass or volume per year	Operator data per facility reported to regulators	DESNZ Energy Statistics	Hydrogen fugitive emissions	mass or volume per year	NIEA) via measurement or estimation methods.	
	SMR/ATR+CC	Hydrogen produced	mass or volume per year	Operator data per facility reported to regulators	DESNZ Energy Statistics	Hydrogen fugitive emissions	mass or volume per year		
Transportation	**Pipeline - transmission**	Hydrogen transported	mass or volume per year	DESNZ Energy Statistics	Ofgem; NSTA, OPRED, Gas Network operators	Hydrogen fugitive emissions	mass or volume per year	Estimates from research projects or models, e.g. direct from the network operators.	Tier 3, aggregating all facility-level / network / fleet emissions data; the AD collected here are for info, to enable QC against DUKES / other data.
	Pipeline - distribution	Hydrogen transported	mass or volume per year	DESNZ Energy Statistics	Ofgem; NSTA, OPRED, Gas Network operators	Hydrogen fugitive emissions	mass or volume per year	Estimates from research projects or models, e.g. direct from the network operators.	
	Container	Hydrogen transported	mass or volume per year	DESNZ Energy Statistics	Ofgem; NSTA, OPRED, Gas Network operators	Hydrogen fugitive emissions	mass or volume per year	Estimates from research projects or models, e.g. direct from the fleet operators.	
Storage	**Salt Cavern**	Hydrogen stored	mass or volume per year	DESNZ Energy Statistics	Data from operators or regulators	Hydrogen fugitive emissions	mass or volume per year	Operator data per facility e.g. reported to regulators (EA, SEPA, NRW,	Tier 3, aggregating all facility-level emissions data; the AD collected here are for info, to enable QC against DUKES / other data.

		Activity Data				Emission Factors			Model requirements
Value Chain Step	**Sub-step / application**	**Activity**	**Units**	**Proposed data source**	**Cross-check / additional source**	**EF**	**Units**	**Proposed data source**	
								NIEA) via measurement or estimation methods.	
	Above Ground	Hydrogen stored	mass or volume per year	DESNZ Energy Statistics	Data from operators or regulators	Hydrogen fugitive emissions	mass or volume per year	Operator data per facility e.g. reported to regulators (EA, SEPA, NRW, NIEA) via measurement or estimation methods.	
Use	**Gas turbines**	Hydrogen used	mass or volume per year	Operator data per facility reported to regulators	DESNZ Energy Statistics	Hydrogen fugitive emissions	mass or volume per year	Operator data per facility e.g. reported to regulators (EA, SEPA, NRW, NIEA) via measurement or estimation methods.	Complex model to combine the best available direct emission estimates from each sub-source. Some elements (e.g. gas turbines, industrial sites) might be Tier 3, aggregating all facility-level emissions data; for sectors such as commercial, residential it is much more difficult to envisage such a direct measurement / estimate method but perhaps a combination of Tier 3 for larger (commercial) sites and then Tier 2 using EFs for UK circumstances for smaller users will become feasible. The AD collected here are for info, to enable QC against DUKES / other data.
	Domestic/Commercial	Hydrogen used	mass or volume per year	DESNZ Energy Statistics	Data from researchers, trade associations, consumers	Hydrogen fugitive emissions	mass or volume per year	Estimates from research projects or models, e.g. direct from equipment suppliers, researchers.	
	Process	Hydrogen used	mass or volume per year	Operator data per facility reported to regulators	DESNZ Energy Statistics	Hydrogen fugitive emissions	mass or volume per year	Operator data per facility e.g. reported to regulators (EA, SEPA, NRW, NIEA) via	

		Activity Data				Emission Factors			Model requirements
Value Chain Step	**Sub-step / application**	**Activity**	**Units**	**Proposed data source**	**Cross-check / additional source**	**EF**	**Units**	**Proposed data source**	
								measurement or estimation methods.	
	Fuel cell	Hydrogen used	mass or volume per year	DESNZ Energy Statistics	Data from researchers, trade associations, consumers	Hydrogen fugitive emissions	mass or volume per year	Estimates from research projects or models, e.g. direct from equipment suppliers, researchers.	
	Internal combustion	Hydrogen used	mass or volume per year	DESNZ Energy Statistics	Data from researchers, trade associations, consumers	Hydrogen fugitive emissions	mass or volume per year	Estimates from research projects or models, e.g. direct from equipment suppliers, researchers.	

F.2 Grey and blue hydrogen production

Table F.4:Indicative improved approach, grey and blue hydrogen production

		Activity Data				Emission Factors			Model requirements
Value Chain Step	**Sub-step / application**	**Activity**	**Units**	**Proposed data source**	**Cross-check / additional source**	**EF**	**Units**	**Proposed data source**	**Model requirements**
Production	**SMR/ATR (grey)**	Feedstock used and carbon content	mass or volume per year	Emissions Trading Scheme	Data from operators or regulators, from DESNZ energy statistics	CO_2 generated and CO_2 captured	mass or volume per year	ETS, Pollution inventories under EPR/IED	The precise method will depend on the methods deployed by operators within reporting systems such as ETS (e.g. mass balance approaches, point of process/combustion methods). Calculations may be conducted across the existing NAEI, ETS and regulatory inventory pre-processing models, with the final emission calculations then completed in a new standalone hydrogen production model.
	SMR/ATR+CC (blue)	Feedstock used and carbon content	mass or volume per year	Emissions Trading Scheme	Data from operators or regulators, from DESNZ energy statistics	CO_2 generated and CO_2 captured	mass or volume per year	ETS, Pollution inventories under EPR/IED	

F.3 Hydrogen combustion and hydrogen fuel cells

Table F.5: Indicative initial approach, hydrogen combustion and hydrogen fuel cells

		Activity Data				Emission factors			Model requirements
		Activity	**Units**	**Proposed data source**	**Cross-check/ additional source**	**EF**	**Units**	**Proposed data source**	
Use	**Gas turbines**	Hydrogen combusted	mass or volume per year	DESNZ Energy Statistics	Data from operators or regulators	Priority is for NOx emissions	kt NOx per unit AD (i.e. per unit mass or volume)	Operator data per facility reported to regulators (EA, SEPA, NRW, NIEA). EMEP/EEA latest guidebook for non-reporting facilities.	A new model to derive hydrogen activity data per source category, derived from DUKES and data inputs such as UK ETS. For high emitting permitted installations, part pre-processed via the RIDB, ETS and then within industry-specific NAEI models. For small-scale combustion sources,

		Activity Data				Emission factors			Model requirements
		Activity	**Units**	**Proposed data source**	**Cross-check/ additional source**	**EF**	**Units**	**Proposed data source**	
									data handled via existing NAEI models, e.g. through the addition of EFs pertinent to hydrogen combustion source-activity (per technology, for pure hydrogen and fuel blends) combinations via the EFDB model.
	Industrial processes	Hydrogen combusted	mass or volume per year	DESNZ Energy Statistics	Data from operators or regulators	Priority is for NOx emissions	kt NOx per unit AD (i.e. per unit mass or volume)	Operator data per facility reported to regulators (EA, SEPA, NRW, NIEA). EMEP/EEA latest guidebook for non-reporting facilities.	A new model to derive hydrogen activity data per source category, derived from DUKES and data inputs such as UK ETS. For high emitting permitted installations, part pre-processed via the RIDB, ETS and then within industry-specific NAEI models. For small-scale combustion sources, data handled via existing NAEI models, e.g. through the addition of EFs pertinent to hydrogen combustion source-activity (per technology, for pure hydrogen and fuel blends) combinations via the EFDB model.
	Domestic / commercial	Hydrogen combusted	mass or volume per year	DESNZ Energy Statistics	Data from researchers, trade associations, consumers	Priority is for NOx emissions	kt NOx per unit AD (i.e. per unit mass or volume)	EMEP/EEA 2023 Guidebook	Can be handled via existing NAEI models, e.g. through the addition of EFs pertinent to hydrogen combustion source-activity (per technology, for pure hydrogen and fuel blends) combinations via the EFDB model.
	Transportation	Hydrogen combusted or used in fuel cells	mass or volume per year	DESNZ Energy Statistics	Data from researchers, trade associations, consumers	Priority is for NOx emissions	kt NOx per unit AD (i.e., per unit mass or volume)	EMEP/EEA 2023 Guidebook	Additional EFs via the NAEI road transport database.

Table F.66: Indicative improved approach, hydrogen combustion and hydrogen fuel cells

		Activity Data				Emission factors			Model requirements
		Activity	**Units**	**Proposed data source**	**Cross-check/ additional source**	**EF**	**Units**	**Proposed data source**	
Use	**Gas turbines**	Hydrogen combusted	mass or volume per year	DESNZ Energy Statistics	Data from operators or regulators	Priority is for NOx emissions	kt NOx per unit AD (i.e. per unit mass or volume)	Develop UK-specific EFs from research such as the Industrial Accelerator Programme demonstration projects (if used in gas turbines) or other innovation programmes. Reported NOx from first plants starting operation, through established reporting requirements to regulatory bodies (e.g. IED/PRTR covered installations).	Current NAEI models to be extended to accommodate the new data streams from both high emitting permitted installations (RIDB) and to impute EFs from a new range of small-scale hydrogen combustion technologies/sectors alongside a new hydrogen activity data model.
	Industrial processes	Hydrogen combusted	mass or volume per year	DESNZ Energy Statistics	Data from operators or regulators	Priority is for NOx emissions	kt NOx per unit AD (i.e. per unit mass or volume)	Develop UK-specific EFs from research such as the Industrial Accelerator	Current NAEI models to be extended to accommodate the new data streams from both high emitting permitted installations (RIDB) and to impute EFs from a new range of small-scale hydrogen combustion

		Activity Data				Emission factors			Model requirements
		Activity	**Units**	**Proposed data source**	**Cross-check/ additional source**	**EF**	**Units**	**Proposed data source**	
								Programme demonstration projects.	technologies/sectors alongside a new hydrogen activity data model. For high emitting industrial applications, potentially a need to redesign existing NAEI models to integrate hydrogen-fired units into data flow.
	Domestic / commercial	Hydrogen combusted	mass or volume per year	DESNZ Energy Statistics	Data from researchers, trade associations, consumers	Priority is for NOx emissions	kt NOx per unit AD (i.e. per unit mass or volume)	Develop UK-specific EFs from research, e.g. Imperial College COSH-AIR study, Village or town level hydrogen usage trials (e.g. H100)	Current NAEI models to be extended to accommodate the new data streams, to impute EFs from a new range of small-scale hydrogen combustion technologies/sectors alongside a new hydrogen activity data model.
	Transportation	Hydrogen combusted or used in fuel cells	mass or volume per year	DESNZ Energy Statistics	Data from researchers, trade associations, consumers	Priority is for NOx emissions	kt NOx per unit AD (i.e. per unit mass or volume)	Develop UK-specific EFs from research, e.g. Imperial College COSH-AIR study, vehicle manufacturers and performance tests.	Current NAEI models to be extended to accommodate the new data streams, to impute EFs from a new range of transport combustion technologies/sectors alongside a new hydrogen activity data model.

F.4 Ammonia Fugitive emissions

Table F.7:Indicative initial approach, ammonia fugitive emissions

		Activity Data				Emission factors			Model requirements
		Activity	**Units**	**Proposed data source**	**Cross-check/ additional source**	**EF**	**Units**	**Proposed data source**	
Production	**Hydrogen to ammonia production processes**	Ammonia produced	mass or volume per year	DESNZ Energy Statistics	Data from operators or regulators	Ammonia fugitive emissions	% by volume or mass	No data sources identified yet, further research in this area is needed	A new model to derive ammonia activity data per source category, derived from DUKES and data inputs such as ETS. For high emitting permitted installations, part pre-processed via the RIDB, ETS and then within industry-specific NAEI models. For small-scale combustion sources, data handled via existing NAEI models, e.g. through the addition of EFs pertinent to hydrogen combustion source-activity (per technology, for pure hydrogen and fuel blends) combinations via the EFDB model.
Transport	**Ammonia transport**	Ammonia transported	mass or volume per year	DESNZ Energy Statistics	Data from researchers, trade associations, consumers	Ammonia fugitive emissions	% by volume or mass	No data sources identified yet, further research in this area is needed	
Storage	**Ammonia storage**	Ammonia stored	mass or volume per year	DESNZ Energy Statistics	Data from researchers, trade associations, consumers	Ammonia fugitive emissions	% by volume or mass	No data sources identified yet, further research in this area is needed	

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