Department for
Business, Energy
& Industrial Strategy

H2 EMISSION POTENTIAL LITERATURE REVIEW

E4tech (UK) Ltd for the Department for Business Energy and Industrial Strategy (BEIS)

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H2 Emission Potential Literature Review

Final report

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1. Introduction

BEIS is aiming to strengthen the evidence base on the potential long-term approaches to decarbonising energy for heating. One option being explored is the use of hydrogen in place of natural gas in the gas grid to provide low carbon heat. In order to assess the viability of this approach BEIS needs to understand the types and rates of emissions associated with its production, distribution and end-use. Therefore this study aimed to capture and assess the current knowledge of the potential emissions types and rates in a hydrogen-for-heating decarbonisation scenario. It focusses on six key research questions (RQs) and identifies gaps in the evidence that may inform future research. These research questions are of particular interest to BEIS as they will enable assessment of the climatic, health and environmental impacts of hydrogen used in heating, and were selected by BEIS to enhance understanding and address identified evidence gaps.

A thorough search across all of the topics of interest was carried out in both the grey and academic literature. Over 250 studies were obtained, which were then narrowed down to a long-list of 148 relevant sources. Of the sources in the long-list, those most relevant to the aims of this study underwent quality assessment (QA) according to BEIS's quality assessment procedures (see Appendix B). Out of the 148 relevant sources, 116 sources underwent quality assessment, of which 109 passed. A total of 36 sources were then selected for detailed review on the basis of the QA score awarded, how current the research is, eminence of author or organisation in the field, and relevance to the key research questions.

The information within these sources was reviewed and compared, and where possible key assumptions made in each source were noted, and an assessment made of the level of uncertainty in the information and underlying reasons for differences between sources. For each of the key research questions, conclusions were drawn, where appropriate, based on the balance of evidence, evidence gaps were highlighted, and priority areas for future work were suggested. The report is structured around the hydrogen value chain, covering upstream emissions, emissions from hydrogen production, and emissions from hydrogen transport and end-use. Within this structure we assess the state of the evidence, whether it is applicable to a UK hydrogen for heating scenario, and whether it is robust enough for policy-making. We also identify areas of concern and make recommendations for how these could be addressed. These conclusions are summarised in the Summary of Findings, including tables of aggregated data, with full data tables provided in annexes.

2. Objectives and structure of report

The overall project aims, were as follows: 1) To capture and assess the current evidence for the potential emissions types and rates in a hydrogen-for-heating decarbonisation scenario; and 2) to identify gaps in this evidence that may inform future research. The analysis was guided by a set of key research questions:

- RQ1: What are the potential H_2 leakage rates at the hydrogen production stage via steam methane reformation (SMR) with carbon capture, coal & bio gasification with carbon capture and electrolysis?
- RQ2: What are the potential wider fugitive emission types and rates from H_2 production via SMR with carbon capture coal & bio gasification with carbon capture and electrolysis, including but not limited to: methane, nitrous oxide, carbon monoxide, hydrogen sulphide, carbon dioxide, sulphur oxides (SO_x), nitrogen oxides (NO_x), mercury and other metals, particulate matter (PM_{10} and $PM_{2.5}$), carbonyl sulphide)? (In addition, BEIS indicated interest in Sulfur hexafluoride (SF6), Tetrafluoroethane (HFC134a), Non-methane volatile organic compounds (NMVO C), and steam.)
- RQ3: What are the potential fugitive H_2 emission rates post-production (transmission to end-use) with distribution via the gas grid?
- RQ4: What are the upstream/well-to-tank carbon emissions of using coal as a hydrogen input fuel?
- RQ5: For each of the questions above, what is the technical and commercial potential for abatement of these emissions?
- RQ6: Which research papers have explored upstream/well-to-tank non-carbon emissions from using natural gas, coal and biogas as hydrogen input fuels?

For each of the research questions, E4tech sought to review and synthesize the existing evidence base, including industry and academic literature, on the potential emission sources, types and rates in a hydrogen-for-heating UK decarbonisation scenario. Within the literature E4tech aimed to capture: a) what the state of the evidence is, b) what assumptions were used in any analysis, c) whether the studies are consistent or disagree, and provide judgement as to whether the uncertainty is real or misplaced, d) any key evidence gaps, e) where are the key areas of concern, f) conclusions that can be drawn based on the balance of evidence, and g) what, if any, are the priority areas that future work should focus on.

The review was focused primarily on drawing out findings relevant to Great Britain but drew significantly on a wide range of evidence, including from the UK and internationally. Analysis was focused on certain specific parts of the value chain, reflecting key priorities for BEIS, but an effort was made to provide BEIS with a broad perspective on the literature across the value chain and emissions types. The searches were, therefore, designed not to be exhaustive but to provide at least one output in as many of the research questions as possible.

Agreed priority areas included hydrogen production emissions, and leakage rates from the gas grid (primarily hydrogen), including both pure hydrogen and hydrogen blend scenarios. Upstream emissions were given a lower priority with emphasis to be placed on coal and natural gas. Equal emphasis was placed on GHG and non-GHG emissions during the literature searches. Where data on leakage from storage and emissions from other transport means were reported these were also included.

The report provides a summary of the findings from the research and is intended to offer an overview of the state of knowledge relevant to a hydrogen for heating decarbonisation scenario. It highlights areas where a significant body of knowledge already exists but, perhaps more importantly, points to areas where knowledge is lacking. This should offer underpinning evidence for where future research effort could be directed. The scope of this project was limited in time and in budget, therefore whilst every effort has been made to cover BEIS' key research questions, it is possible that additional information is available that has not been considered within this study. Only a comprehensive literature review could resolve this.

In addition to the narrative of the report, a database containing the long-list of sources is provided, comprising basic information on the source, quality assessment score, and identification of those reviewed in detail. Details of the searches performed are also included so that these can be replicated by BEIS if required. Throughout the report, sources within the longlist are referred to as (Author, date), and those which are not in the long-list (for example they offer supporting or less relevant information) are provided in footnotes.

The report is structured as follows: in section 3 a description of the methodological approach to the literature search is provided; in section 4 detailed results are presented in sub-sections broadly following the value chain. Additional material is provided in the Appendices.

3. Methodology

This section briefly outlines the methodology used for this study, which is summarised in Figure 1.

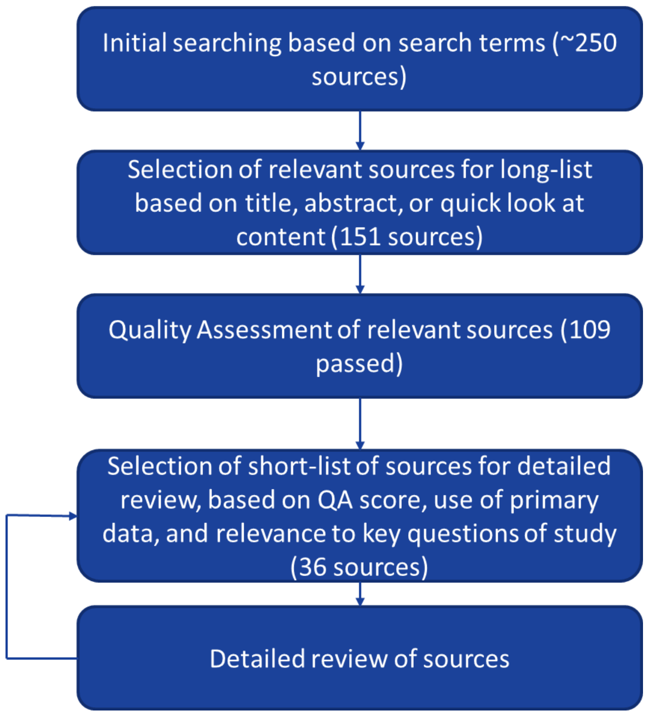

Figure 1 Outline of methodology followed for this study

Initially, a thorough search across all of the topics of interest was carried out in both the grey and academic literature, which comprised the keywords noted in Table 10 and focussed predominantly on literature from the past 10 years. Initial searches produced well over 1000 results, which provided roughly 250 sources, which were then narrowed down to a long-list of 148 based on their relevance to this study. This long-list of sources is provided in Appendix C, and all information is provided in a separate excel database.

Search terms used in grey literature	Search terms used in academic literature
Hydrogen electrolysis emissions Electrolysis hydrogen LCA Hydrogen natural gas emissions Hydrogen natural gas LCA Hydrogen distribution emissions Hydrogen pipeline emissions Hydrogen production air quality Hydrogen methane air quality Hydrogen production VOC Air quality hydrogen Hydrogen coal LCA	hydrogen AND emissions AND production AND electrolysis hydrogen AND emissions AND production AND "steam methane reforming" hydrogen AND emissions AND production AND biogas hydrogen AND emissions AND production AND "coal gasification" hydrogen AND emissions AND production AND "biomass gasification" hydrogen AND emissions AND pipeline hydrogen AND emissions AND boiler hydrogen AND leakage AND pipe hydrogen AND fugitive hydrogen AND production AND leak* hydrogen AND SOx and smr hydrogen AND SOx smr AND SOx smr AND NOx "steam methane" AND SOx "natural gas" AND reform* AND SOx "natural gas" AND reform* AND NOx

Summary of search terms used in literature review

Of the sources in the longlist, those relevant to the aims of this study underwent quality assessment according to BEIS's quality assessment procedures (Appendix B) to give them a score ranging from 0 to 9. Sources which received 6 or above were considered to pass the QA. 116 sources underwent quality assessment, of which 109 passed.

The database of sources, including basic information such as title, author, Uniform Resource Locator (URL) etc. and the results of the quality assessment were provided to BEIS as a deliverable, and this information is summarised in Appendix C.

In the second half of the study, 36 sources were chosen for detailed review. These were chosen on the basis of the QA score, how current the research is, eminence of author or organisation in the field, and perceived relevance to this study. There was an element of iteration in this, in that some sources were discarded from the detailed review and others included, once their content had been reviewed. These sources are summarised in Appendix A, Table 13.

The time constraints of the project limited the detailed review to 36 sources, and the choice of these was based on the best information available at the time of choosing these sources. Therefore the information presented here is not a comprehensive review of all literature around these topics, but aims to present key conclusions from a number of authoritative works, and highlight gaps in the literature where these exist.

The detailed source review was carried out in order to answer the key research questions outlined in section 2, structured according to upstream emissions, emissions from hydrogen production, emissions from hydrogen transport, and emissions from end-use of hydrogen (Figure 2). All emissions figures provided in this study are given in g/kWh_{HHV} hydrogen, unless explicitly stated.[1]

The literature review is structured in order to most effectively answer the key research questions (section 2). Therefore the emissions from the entire hydrogen value chain have been split up into upstream emissions, emissions from hydrogen production, emissions from hydrogen transport, and emissions from hydrogen end-use. The scope of these categorisations is summarised in Figure 2

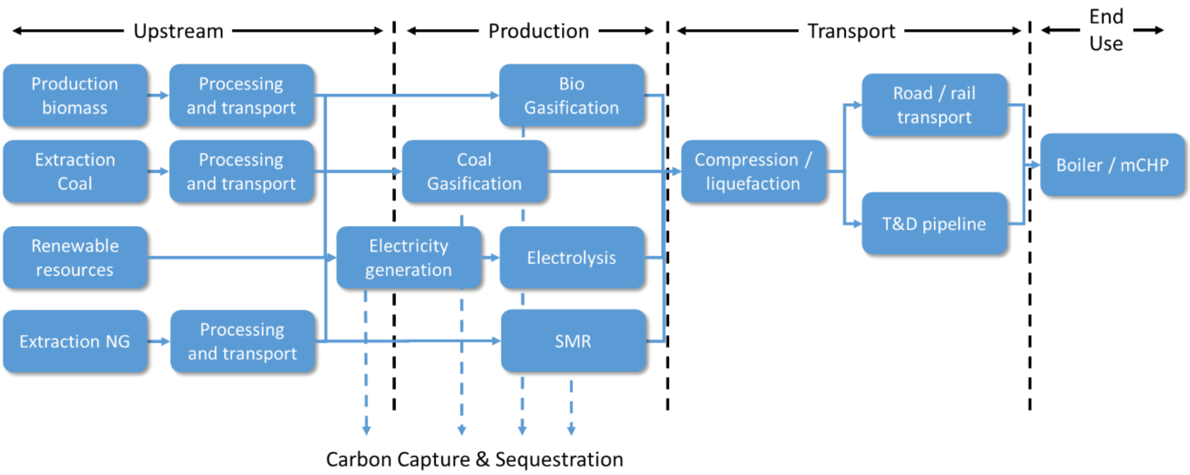

Figure 2 Illustration of hydrogen energy chain

Within this study, electricity for electrolysis is included within the ‘emissions from hydrogen production’ (section 4.3), although it could also be argued that it fits into ‘upstream emissions’. This approach was chosen because electricity was not within scope of RQ6 or RQ4, which address upstream emissions.

3.1 Life Cycle Assessment databases

Many of the papers assessed in this study were life cycle assessments (LCAs). In LCA, a ‘life cycle inventory’ of all of the material and energy inputs and outputs required to produce a particular product is put together. The impact of each input / output in a number of ‘impact categories’ is then quantified, to give an overall impact per unit of product produced. As a simple example, emissions of CO_2, CH_4 and N_2O each have an impact on the ‘global warming potential’ in terms of g substance/g CO_2eq. so the final impact is presented in terms of gCO_2eq./unit of product, rather than quantifying each individual species emitted from the process.

[1] If emissions in a paper were given in another unit, they were converted to an energy basis using the HHV of hydrogen of 141.86MJ/kg. For papers where the emissions were given in g pollutant / kWH_{LHV} hydrogen, these were converted to a per HHV basis using the ratio of the hydrogen HHV / hydrogen LHV, which is roughly 1.18.

When conducting life cycle assessment of complex processes, it is common practice to obtain some data from LCA databases. Ecoinvent[2] is an example of an LCA database. These databases hold data on the life cycle inventory (i.e. all of the material and energy inputs and outputs) of many common products, and may be accessed through a software tool such as SimaPro or GaBi. The user must have a license to use the underlying data, and is not allowed to publish or disseminate significant proportions of the database.[3] A LCA 'methodology' is then used in order to evaluate the impact of all of the emissions on a number of 'impact categories' such as Global Warming Potential or Acidification. For the upstream emissions from natural gas and coal, some information is provided in this study from Ecoinvent. The entries within the database are generally specific to a particular geographic area, so an entry specific to the UK would be available for some products, whist in most cases an entry specific to Europe or Western Europe would be the most applicable data entry to the UK. Whilst the data from Ecoinvent could be used in BEIS models, it would require a detailed understanding of what was being modelled and it would be a separate project in itself to extract and review the correct data from Ecoinvent. Each entry should be thoroughly reviewed to ensure that it is up to date, representative of the exact product or process which is of interest, and some manipulation within the software may be required to ensure that the scope of emissions matches that required by BEIS.

The GREET[4] model is also referred to several times throughout this report. GREET is a full life cycle model developed by the Argonne National Laboratory in the USA which evaluates emissions from the full life cycle of a vehicle production, use (including fuel production) and disposal. The model calculates life cycle emissions in CO_2eq. from the emissions of CO_2, CH_4 and N_2O. In addition, emissions of six pollutants are calculated: volatile organic compounds (VOCs), carbon monoxide (CO), nitrogen oxide (NOx), airborne particulate matter with sizes smaller than 10 micrometre (PM10), particulate matter with sizes smaller than 2.5 micrometre (PM2.5), and sulfur oxides (SOx). Emissions from hydrogen production are included within GREET, but in general it is more transparent to obtain data from the underlying sources (e.g. Young et al., 2017). Nevertheless GREET is open-access and could be used by BEIS to obtain information on the emissions associated with hydrogen production from natural gas, electrolysis, coal and biomass. This is not within scope of this literature review as it would require definition of many parameters of the hydrogen production process, and some changes to the model including for example adding grid emissions specific to the UK.

4. Summary of findings

4.1 Upstream emissions

The following section covers 'upstream emissions', which are the emissions generated from processes before the hydrogen production process: principally input fuel extraction and processing.

[2] Wernet, G., Bauer, C., Steubing, B., Reinhard, J., Moreno-Ruiz, E., and Weidema, B., 2016. The ecoinvent database version 3 (part I): overview and methodology. The International Journal of Life Cycle Assessment, [online] 21(9), pp.1218–1230. Available at: <http://link.springer.com/10.1007/s11367-016-1087-8>
[3] Ecoinvent (n.d.) Ecoinvent End User Licence Agreement, Available from: https://www.ecoinvent.org/database/terms-of-use---eula/terms-of-use---eula.html
[4] Greenhouse gases, Regulated Emissions, and Energy use in Transportation

4.1.1 Natural gas

There is substantial literature on the upstream GHG emissions from natural gas production and whilst the range of figures quoted is wide, it is possible to find figures specific to the UK which may be appropriate in policy-making. These UK-specific figures represent an average of many possible different natural gas production and delivery pathways, which may in turn have a wide range of emissions. In particular, liquefied natural gas (LNG) transported over long distances generally has substantially higher emissions than natural gas (NG) in gaseous form transported small distances by pipeline. In consequence, if the amount of LNG compared to domestically produced gas used in the UK increases in the future, then average upstream natural gas emissions will increase.

Non-GHG emissions from natural gas used in hydrogen production are less widely reported, and no sources were found that were specific to the UK.

Exergia, COWI and E3M (2015) calculate, based on extensive collection of measured data, that upstream GHG emissions from NG in the EU vary between 8.25 and 54.96 $gCO_2eq./kWh_{natural\ gas}$ when transport is excluded, and that for gas used in the UK the average figure is 17.81 $gCO_2eq./kWh_{natural\ gas}$.

In a major literature review covering 424 sources, Balcombe et al. (2015) report that within these sources GHG emissions for NG are between 9.72 and 118.08 $gCO_2eq./kWh_{natural\ gas}$ when transport is included. For LNG, upstream emissions lie between 25.2 and 208.8 $gCO_2eq./kWh_{natural\ gas}$ including transport. The data from other sources (Sadler et al., 2016 and Edwards et al., 2014) fits within this range. The data provided by Balcombe et al. is based on a review of global literature, most of which is applicable to the USA, so it is possible that a narrower uncertainty range could be obtained if the natural gas supply specific to the UK was examined.

This large range of emissions is due mostly to real differences in how the gas is produced: variation in the production method (onshore, offshore, conventional or unconventional) of the gas, methane leakage in the supply chain, transport mode and distance, and to a certain extent how emissions (especially methane leakage) are measured. Conversion of these figures from $gCO_2eq./kWh_{natural\ gas}$ to gCO_2eq/kWh_{H2} would depend on the efficiency of hydrogen production.

The analysis also raises questions about how emissions outside of the UK inventory, e.g. emissions from production and liquefaction of natural gas in Qatar, should be taken into account when assessing decarbonisation options.

Disaggregated non-GHG emissions from the sourcing of natural gas used in hydrogen production were reported in two sources, and separate CO_2, CH_4 and N_2O emissions only could be extracted from two other sources (Table 1). There is some variation in these figures, likely due to variations in production method, methane leakage, transport mode and distance, and efficiency of hydrogen production (although this is not always specified in the source). None of the sources are specific to the UK, but could be used to assess at high level which, if any, pollutants are likely to be produced at harmful levels were there to be widespread use of hydrogen for heating in the UK. Comparing reported emissions between those sources which include natural gas transport and those which exclude it suggests that gas transport can be a substantial contributor to the emissions. Given the different ways natural gas could be transported to the UK – by LNG or via pipeline from the North Sea for example – this will be an important factor to define or take into account in any future assessment of emissions in a UK hydrogen for heat scenario. It may be possible to reduce methane emissions (which would also contribute to a reduction in GHG emissions) through the reduction of fugitive methane emissions throughout the natural gas supply chain and not just in the UK (Balcombe et al., 2015).

Reference	**Spath and Mann (2001)**	**Miller et al. (2017)**	**Ramsden et al (2013)**	**Edwards et al (2014)**	
Emissions (mg/kWh_{H2})	**No CCS, gas transport included**	**No CCS, gas transport included**	**No CCS, gas transport included**	**No CCS, gas transport excluded**	**With CCS, gas transport excluded**
CO_2	39,889	21,020	17,429	7338	7617
CH_4	1681	710	1591	403	418
N_2O	0.38	4	0.29	0	0
VOC	-	31	-	-	-
CO	154	101	-	-	-
NOx	282	129	-	-	-
PM10	-	3	-	-	-
PM2.5	-	1	-	-	-
Particulates	13	-	-	-	-
SOx	165	37	-	-	-
Benzene	39	-	-	-	-
NMHC	383	-	-	-	-

Table 1 Summary table: Emissions from the upstream portion of natural gas to hydrogen value chain (NMHC = non-methane hydrocarbons, VOC = volatile organic compounds). “-“ indicates data was not available

Suggested further work: In order to obtain information on the non-GHG emissions from upstream natural gas production in a UK hydrogen for heating scenario, a study specific to the UK could be carried out. Information on the upstream emissions from natural gas production, including non-GHG emissions, is available in LCA databases, but the study would have to carefully define where natural gas is produced, how it is transported, and at what efficiency the SMR process operates in order to obtain figures specifically relevant to a UK hydrogen in heating scenario.

4.1.2 Biomass

Emissions from biomass production are highly varied, depending on the type of biomass, whether it is a waste / residue or not, and assumptions made about land use change. There is a substantial body of existing work on emissions from biomass production, but little that is specific to hydrogen production from biomass. In general, the use of average emissions from 'biomass production' does not provide an adequate basis for policy-making, given that emissions vary substantially depending on the crop, cultivation method, location, land type etc.

Non-GHG emissions: The non-GHG impacts of biomass production have been addressed in LCA studies of liquid fuel production from biomass, but only one study was found (Miller et al., 2017) which specifically considered hydrogen production from biomass. This source provided figures for VOC, CO, NOx, particulates and SOx emissions in $g/kWh_{H2,}$ calculated using GREET. However, this single study is not specific to the UK and covers a limited number of emission types, so the figures presented are not considered robust for UK policy making.

Emission	Emissions from biomass feedstock (g/kWh_{H2})
CO_2 (fossil only)	15.4
CH_4	0.030
N_2O	0.046
VOC	0.015
CO	0.033
NOx	0.082
PM10	0.0061
PM2.5	0.0030
SOx	0.040

Table 3 Emissions from the production of biomass feedstock used in the production of hydrogen via gasification; ; assuming overall thermal efficiency of biomass gasification to gaseous hydrogen ($kWh_{H2}/kWh_{biomass}$) of 57% (Miller et al. (2017).

4.1.3 Coal

Coal production is a well-established commercial process with an extensive evidence base on associated emissions. The reported greenhouse gas (GHG) emissions rates vary substantially and this is likely due to real-world differences in the type of coal and how it is produced, e.g. geography, mining technique, and the energy content of the coal being mined. Non-GHG emissions are evaluated in full life-cycle assessments of coal to hydrogen pathways, but it was not possible to extract data specifically associated with upstream coal production from the sources examined.

GHG emissions: Based on three sources, GHG emissions from upstream coal production ranged from 32 to 60 gCO2eq./$kWh_{coal.}$ The upstream GHG emissions associated with coal production in the UK have been estimated (Hammond et al., 2013, based on the National Atmospheric Emissions Inventory) to be 60gCO_2eq./$kWh_{coal.}$ However it is likely that in reality there is a considerable range around this figure, given that in the USA the emissions from coal extraction could range from 32 to 54 gCO_2eq./kWh_{coal} (Scull et al., 2017). This wide range of values reflects differences in the types of coal and how it is produced, as noted above. For example, surface mining generates higher CO_2 emissions due to land-use change, and underground mining generates significantly higher CH_4 emissions due to the release of coal bed methane, though it is less land intensive (Scull et al. 2017)[5].

[5] http://mpaenvironment.ei.columbia.edu/files/2014/06/UpstreamEmissionsReport_SIPA_REVISED.pdf

The upstream GHG emissions arising from the sourcing and transportation of coal used in the coal to hydrogen process (in g/kWh$_{H2}$) can be extracted from Ramsden et al. (2013) and Edwards et al. (2014) (Table 4). However, the utility of these two studies for this work appears limited since they a) show markedly different emission rates, and b) the applicability to the UK is unclear given the studies are based in different locations[6], and c) will be affected by the efficiency of the coal-to-hydrogen process, which is stated as 56.8% for Ramsden but not reported in Edwards.

The Edwards et al. figures highlight that upstream emissions in g/kWh$_{H2}$ may increase with the introduction of carbon capture and storage during hydrogen production. This is due to increases in the amount of input fuel required when CCS is used. Additional heat and electricity are required during the CCS process, which Edwards assumes will be provided by the coal thereby increasing the upstream emissions in g/kWh$_{H2}$. It may be possible to mitigate this impact by using low carbon sources of heat and electricity, though assessing the technical and commercial feasibility of this and the extent of potential mitigation was not examined in the sources.

	Emissions (g/kWh$_{H2}$)		
Species	**With CCS (Ramsden et al., 2013)**	**With CCS (Edwards et al., 2014)**	**Without CCS (Edwards et al., 2014)**
CO_2	3.2	44	38
CH_4	0.54	2.9	2.5
N_2O	0.0001	0.0018	0.0015

Table 4 GHG emissions from coal production (Ramsden et al., 2013, Edwards et al., 2014)

Non-GHG emissions: Within the papers reviewed, none reported non-GHG emissions associated with hydrogen production from coal. Several of the papers reviewed in this study carry out full life cycle assessments (LCAs) on routes to hydrogen from coal, for example Dufour (2011), Cetinkaya et al. (2012), and Tong et al. (2015). These were built up based on the full inventory of emissions for upstream coal production but disaggregated emissions for coal production only are not presented within the published papers.

Suggested further work: Overall, the upstream GHG emissions from coal production, in terms of gCO_2eq./kWh$_{coal}$ are well understood. As emissions vary quite widely depending on the type of coal and production method used, an appropriate figure would need to be used to obtain an accurate estimate of the likely emissions arising from a future hydrogen for heating scenario. In addition, the efficiency of the hydrogen production and CCS process, and other key assumptions, would need to be defined to obtain a figure in gCO2eq./kWhH2. Similarly, information on the upstream non-GHG emissions from coal production could be obtained from LCA databases to identify upstream coal emissions data specific to a UK hydrogen for heating scenario, with relevant assumptions and system boundaries chosen that could provide a more accurate assessment of emissions for the UK context**.**

[6] Ramsden et al. is focussed on the USA whereas Edwards et al. is focussed on Europe

4.2 Emissions from hydrogen production

4.2.1 Electrolysis

The emissions from hydrogen production by electrolysis are comprised of those from the production of electricity required for electrolysis (including construction and operation of the generating and / or transmission and distribution equipment), and those from the electrolysis plant itself (both construction and operation of the electrolyser).

Data is available on the emissions from hydrogen generated by electrolysis, but none of the sources are directly comparable because of differences in scope, e.g. electricity source, and electrolyser type (alkaline, PEM or solid oxide), and assumptions made around lifetime and load factor. All of these factors can have a significant impact on the level of emissions.

GHG emissions: The GHG emissions of hydrogen produced by electrolysis depend substantially on how the electricity was generated. The GHG intensity of the grid in the UK has been decreasing year on year.[7] Embodied emissions for hydrogen production via grid-fed electrolysis in the UK will fall as assuming that the grid decarbonises. Although renewable electricity can be zero or very low emission at the point of generation, emissions are associated with the construction of the infrastructure. Evidence from Spath and Mann (2004) shows that these can be significant and should be accounted for.

Ramsden et al. (2013), Aleknavicute et al. (2016) and Edwards et al. (2014) assume the GHG emissions from electrolyser operation to be zero. Other studies show that construction emissions can be significant: e.g. Mori et al. (2014) calculate from an LCA study that the GHG emissions from electrolyser construction/operation are 122 $gCO_2eq./kWh_{H2}$, of which 96% result from the manufacture of the electrolyser. A short lifetime and/or low load factor increases the proportionate contribution of electrolyser construction emissions to the overall GHG emissions per unit of hydrogen. The contribution of construction emissions may differ between alkali, PEM and solid oxide electrolysers, and may reduce as these technologies and production methods develop. Whilst inputs to the operation of alkaline and PEM electrolyser are generally limited to a small amount of auxiliary power, solid oxide electrolysers require heat to keep them at their optimum operating temperature and how this heat is provided can substantially impact the overall GHG emissions from the electrolyser operation. Mehmeti et al. (2017) calculates from an LCA study that the operational GHG emissions from a solid oxide electrolyser are 119 $gCO_2eq./kWh_{H2,}$ of which 87% are attributed to the heat required by the cell to operate. Use of a low-carbon or waste heat source would decrease emissions.

Non-GHG emissions: Non-GHG emissions from hydrogen production by electrolysis are reported by Spath and Mann (2004) and Miller (2017) and the data are presented in Table 5 and Table 6 respectively. Whilst some general conclusions can be drawn from these data, the divergence in scope and lack of direct applicability to the UK means that limited conclusions can be drawn.

Spath and Mann (2004) allow comparison of the non-GHG emissions from the production of electricity from wind power, and the emissions from the electrolysis process itself, including the

[7] Staffell, I, Green R, Gross R and Green T, 2018)[7] Electric Insights Report. Imperial College, London. Available at http://electricinsights.co.uk/#/reports/report-2017-q4/overview?_k=ogyf3p

emissions from construction of the wind turbines and the electrolyser (Table 5). The authors note that these are the 'major air emissions' rather than providing a comprehensive list of emissions. According to this source, the largest emissions are NOx and SOx which are due to the production of benzene used in the manufacture of the electrolyser. As noted above, a short equipment lifetime or load factor will increase the rate of emissions per unit of hydrogen produced. With the exception of NOx and SOx, electrolyser emissions are at least eight times smaller than those from the production of electricity (per unit of hydrogen). However given that this is only one source, and renewable energy technology has moved on significantly since it was published in 2004, it cannot be said with confidence that this assessment would apply to all scenarios.

Emission	Emissions from wind turbine construction and operation (mg/kWh H_2)	Emissions from electrolysis (mg/kWh H_2)
CO2	18,829	1,061
CO	18.3	0.80
CH4	7.0	0.21
NOx	54.7	56.2
Nitrous oxide	0.85	0.071
NMHC	69.8	8.2
Particulates	686	5.1
SOx	95.7	40.4

Table 5 Emissions from the production of hydrogen from wind-generated electricity, covering the production of electricity (including construction and operation of wind turbines) and the electrolysis process (Spath and Mann, 2004)

Miller covers two scenarios, one where solar electricity and the other where USA grid electricity is used for electrolysis. In this study the power required for gasification / liquefaction of the hydrogen are included within scope but emissions from the operation of the electrolyser itself are not included. Few, if any, conclusions can be drawn from this, as the USA grid mix is quite different to that in the UK. Nevertheless it does illustrate that even renewable sources such as solar electricity have emissions associated with manufacture, although these tend to be substantially lower than for grid power with a significant proportion of fossil generation in the mix.

Emission (mg/kWh)	Solar electrolysis (centralised)		USA grid electricity (distributed)	
	Gaseous hydrogen	Liquid hydrogen	Gaseous hydrogen	Liquid hydrogen
CO_2	72346	217468	817931	1020106
CH_4	158	469	1775	2214
N_2O	3.0	6.1	18	21
VOC	9.1	30	113	140
CO	45.7	143.1	533	664
NOx	113	344	1267	1577
PM10	18	52	201	250
PM2.5	12	33	122	152
SOx	158	475	1800	2244

Table 6 Emissions from the production of electricity used in electrolysis (uses USA grid) (Miller et al., 2017)

One source, Mori et al. (2014) reported fugitive hydrogen emissions from an electrolyser: for 57,980 kg of hydrogen produced, 11,960kg of hydrogen is lost to the atmosphere because of system conditioning – a loss of 21%. This figure is based on experiments performed on one particular commercial alkaline electrolysis system[8], where hydrogen losses to the atmosphere ranged between 10% and 25%. This was largely because a portion of the hydrogen was used for system conditioning, and the authors suggest that this high figure could be mitigated by use of a demineralised water feed pump instead. Moreover electrolysers are an established industrial technology, and such high leakage rates are unlikely to be commercially viable, or allowed from a safety point of view. However, no further evidence of hydrogen leakage rates from electrolysis was found in the literature.

Suggested further work: In order to evaluate the emissions produced in a UK hydrogen for heating scenario, a study specific to the UK would be required. In particular if hydrogen is produced from grid electricity, the specific UK grid mix should be included, recognising that this changes over time. Assumptions around electrolyser technology, load factor etc. should be carefully made, recognising that solid oxide electrolysers in particular are still developing technology and require heat energy to operate.

4.2.2 Steam methane reforming

There are a number of technologies for the production of hydrogen from natural gas, with steam methane reforming (SMR) being the most widely deployed method of hydrogen production today. Reported emissions (including those associated with the natural gas source fuel) found in the sources are shown in Table 7. A wide range of sources report the GHG emissions from the SMR process without CCS while only two sources were identified showing the GHG emissions associated with SMR plus CCS. Further research would be needed to obtain data specific to a UK hydrogen for heating scenario. Data on non-GHG emissions is more limited and shows significant variability and, once again, further research on specific UK conditions would be warranted.

GHG emissions: For hydrogen production by SMR without CCS, the CO_2eq. emissions reported across the six different sources identified vary between 222 and 325 gCO_2eq./kWh$_{H2}$. The sources indicate that the majority of these CO_2 emissions are due to the carbon in the natural gas released at the SMR plant, and without CCS they dwarf the GHG emissions at all other points in the natural gas to hydrogen supply chain.

[8] Mori,M., Mrzljak, T., Drobnic, B., Sekavcnik, M. (2013) Integral Characteristics of Hydrogen Production in Electrolysers, Journal of Mechanical Engineering, 59, 10, 585-594

Study reference	Miller (2017)				Spath and Mann (2001)	Young et al. (2017)	Alhamdani (2017)	Susmozas et al. (2013)	Ramsden et al (2013)	Edwards et al. (2014)	
Origin of data	CA-GREET				Literature	Operating SMR plants in the USA	Bottom-up analysis of fugitive emissions + literature data	Aspen-plus simulation	Literature	Literature	
Scope	Excludes construction of infrastructure/ equipment, includes inputs to plant e.g. electricity.				Point emissions from the hydrogen plant only	Point emissions from the hydrogen plant only	Point emissions from the hydrogen plant only	Point emissions from the hydrogen plant only	Excludes construction of infrastructure/ equipment, includes inputs to plant e.g. electricity	Excludes construction of infrastructure/ equipment, includes inputs to plant e.g. electricity	
	Centralised gaseous hydrogen production	Centralised liquid hydrogen production	Distributed gaseous hydrogen production	Distributed liquid hydrogen production						Without CCS	With CCS
CO_2	324,795	478,946	314,858	515,659	225,589	201,365	225,592	215,198	296,295	220,460	36,106
CH_4	411	1182	414	850	0.00	-	5.02	-	631	53	52.7
N_2O	3.0	6.1	3.0	9.1	0.00	-	-	-	1.2	0	0.00
VOC	30.5	51.8	27.4	54.8	-	7.85	-	-	-	-	-
CO	1301	231	119	250	2.03	24.6	-	-	-	-	-
NOx	240.6	478.1	228.4	539.0	22.79	37.54	-	-	-	-	-
PM10	57.9	94.4	54.8	103.5	-	9.22	-	-	-	-	-
PM2.5	48.7	73.1	48.7	76.1	-	8.87	-	-	-	-	-

Particulates	-	-	-	-	0.56	-	-	-	-	-	-
SOx	194.9	511.6	207.1	648.6	0.00	24.91	-	-	-	-	-
NMHC	-	-	-	-	0.00	-	-	-	-	-	-
Benzene	-	-	-	-	0.00	-	-	-	-	-	-
O_2	-	-	-	-	-	-	-	16,749	-	-	-
N_2	-	-	-	-	-	-	-	422,022	-	-	-
H_2O	-	-	-	-	-	-	-	226,618	-	-	-
NO_2	-	-	-	-	-	-	-	0.00	-	-	-

Table 7 Summary of emissions from SMR process, mg/kWh$_{hydrogen}$ (VOC = Volatile organic compounds, NMHC = non-methane hydrocarbons, subset of VOC). All data is for plants without CCS, apart from Edwards et al. as specified

For hydrogen production by SMR with CCS, only two sources were found which give CO_2eq. emissions: 37 or 45 gCO_2eq./kWh_{H2}. Technology for the production of hydrogen from natural gas with CO_2 capture is still under development, with several different process configurations being investigated, so the equivalent CO_2 emissions achieved in practice in the future may well lie outside this range.

Wider emissions: Eight studies were reviewed that quantified wider emissions from hydrogen production by SMR, (see Table 7) and substantial variation between the figures reported is observed. This is partly due to the different scopes of the studies, with a clear divide between those which report only the point emissions from the SMR plant, and those which include also the inputs to the plant, such as electricity, for which emissions are higher.

The available evidence suggests that the main operational emissions from SMR are CO_2, CH_4, N_2O, VOC, CO, NOx, SOx and particulates as these are considered by a number of sources, and emissions of O_2, N_2, N_2O, and H_2O are also provided in one source. However this may not comprehensively cover all emissions, as sources may focus on and report only those which are a priority for their overarching research question, for example they may be limited to GHG or air quality impacts. No information was available on hydrogen leakage from the SMR process, despite additional targeted searching. This is a clear evidence gap.

The variation in terms of the species reported and likely level of emissions reported by the different sources (Table 7) means that this data is not considered suitable for UK policy making. In particular, studies which also include electricity or other inputs (Miller, Ramsden and Edwards) are not applicable to the UK context unless comparative emissions intensities for these inputs could be obtained. Further work could be conducted with the authors of these studies in order to obtain disaggregated figures for the emissions from the SMR plant itself compared to those from electricity, but this level of detail was only publicly available from one source (Spath and Mann, 2001, Table 8). Spath and Mann also report emissions from construction and decommissioning of the SMR plant and while it is not possible to draw concrete conclusions based on this source alone, it does suggest that emissions from construction and decommissioning and SMR plant operation are lower than those from natural gas production and transport – some emissions from the hydrogen plant operation are at least 10 times smaller than those from natural gas production and transport. However, for several species of emissions these elements still contribute a material amount to the overall emissions from hydrogen production.

	Emissions (mg/kWh_{H2})			
Species	**Construction and decommissioning**	**Natural gas production and transport**	**Electricity generation**	**Hydrogen plant operation**
Benzene (C6H6)	0.0	39.4	0.0	0.0
Carbon dioxide (CO_2)	1,078.1	39,889.0	6,738.0	225,588.6

Carbon monoxide (CO)	2.9	153.8	1.0	2.0
Methane (CH_4)	0.0	1,681.4	0.0	0.0
Nitrogen oxides (NOx, as NO_2)	5.6	281.9	29.7	22.8
Nitrous oxide (N_2O)	0.1	0.4	0.6	0.0
Non-methane hydrocarbons (NMHCs)	7.2	382.8	61.8	0.0
Particulates	32.7	12.8	5.9	0.6
Sulfur oxides (SOx as SO_2)	32.5	164.7	60.0	0.0

Table 8 Air emissions from hydrogen production by SMR without CCS (Spath and Mann, 2001). Nb. the column 'natural gas production and transport' refers to upstream natural gas emissions, but is included here for completeness

Of the studies reporting non-GHG emissions types and rates from the SMR production process, only Edwards (2014) considered CCS, and only those species which contribute to global warming potential were reported (Table 7). Therefore there is a distinct lack of data on the likely emission types and rates from SMR with CCS. More detailed information on non-GHG emissions from SMR both with and without CCS is provided in one source (Salkuyeh et al., 2017, Table 9), but these also include emissions from natural gas production which could not be disaggregated to show only operational emissions. Nevertheless, this limited evidence suggests that the introduction of CCS into an SMR plant is likely to increase all non-CO_2 emissions, due to increased energy requirements and the construction of equipment for CO_2 capture, compression and injection. Depending on the CCS technology adopted, emissions relating to the higher energy input requirement could potentially be mitigated using renewable electricity or on-site waste heat for the carbon capture process, but additional emissions from the infrastructure requirements of CCS may be hard to reduce.

		SMR	
Emissions to air	**Unit**	**w/o CC**	**With CC**
CO_2	$g/kWh_{hydrogen}$	279.1	68.5
CH_4	$mg/kWh_{hydrogen}$	474.6	659.8
N_2O	$mg/kWh_{hydrogen}$	7.6	12.7
Volatile organic compounds	$mg/kWh_{hydrogen}$	40.6	55.8
CO,	$mg/kWh_{hydrogen}$	225.9	329.9
Nitrogen oxides	$mg/kWh_{hydrogen}$	299.5	439.0

Particulate matter > 10 microgram	$mg/kWh_{hydrogen}$	40.6	48.2
Particulate matter between 2.5 and 10 microgram	$mg/kWh_{hydrogen}$	40.6	48.2
Sulfur oxides	$mg/kWh_{hydrogen}$	0.21	0.30
Black carbon	$mg/kWh_{hydrogen}$	1.2	2.3
Primary organic carbon	$mg/kWh_{hydrogen}$	2.8	5.6

Table 9 Lifecycle emissions from hydrogen production by SMR both with and without carbon capture (CC) (Salkuyeh et al., 2017). Scope includes emissions from natural gas extraction and transportation, the production of other inputs required for hydrogen production, and the hydrogen production itself. Construction emissions are not within scope.

Suggested further work: For both SMR with and without CCS, additional studies with a UK specific focus could help to narrow down the uncertainty range, although there will still be residual variation depending, for example, on the scale or efficiency of the reformer or type of CCS technology.

Within the context of the overall hydrogen production value chain, non-GHG emissions from the SMR process may be significant, and compared to natural gas extraction there is greater risk of such plants being located to centres of population in the UK. Further work could be carried out in order to obtain information specifically relevant to a UK hydrogen heating scenario. A full LCA could provide information on the quantity of pollutants emitted through the process, or a spatially explicit air quality impacts study could be used to investigate the impacts of these emissions.

4.2.3 Coal gasification

Hydrogen production from coal is operating at commercial scale in some locations in the world today, but is significantly less widespread than the SMR process.

GHG emissions: Three sources reviewed considered the GHG emissions of hydrogen production from coal: Edwards et al. (2014), Ramsden et al. (2013) and Cetinkaya et al. (2012). GHG emissions of hydrogen production from coal gasification reported in these sources ranged from 17 to 144 $gCO_2eq./kWh_{H2}$ with CCS and from 279 to 576 $gCO_2eq./kWh_{H2}$ without CCS. There is not enough information in these studies to say with confidence why these figures cover such a wide range, although it could be due to variations in the coal composition and the gasification technology used. The GHG emissions of coal gasification with CCS are also impacted by the amount of additional energy required (often expressed as a reduction in the overall efficiency of the process) and percentage of CO_2 captured.

Given the wide range of reported GHG emissions, and lack of information about the technologies on which they are based, these figures are not considered robust.

Non-GHG emission: A limited number of point-source emissions from a coal gasifier were quantified by Dufour et al. (2011), and CO_2, CH_4 and N_2O emissions from the process (including additional inputs such as electricity) were quantified by Ramsden et al (2013) and Edwards et al. (2014), as summarised in Table 10. These are not comprehensive: Ramsden and Edwards include only those emissions which contribute to global warming, and Dufour states that only the 'main' emissions from the gasifier are accounted for. No sources were found which reported fugitive hydrogen emissions from the process, despite additional targeted searching.

	Emissions (g/kWh_{H2})			
Species	**With CCS (Ramsden et al., 2013)**	**With CCS (Edwards et al., 2014)**	**Without CCS (Edwards et al., 2014)**	**Without CCS (Dufour et al., 2011)**
CO_2	131	17.2	576	-
CH_4	0.556	0	0	-
N_2O	0.00088	0	0	-
Particulates	-	-	-	2.26
NOx	-	-	-	1.64
SOx	-	-	-	0.82

Table 10 Emissions to air from hydrogen production by coal gasification. Dufour includes point source emissions from the gasifier only, whilst Edwards and Ramsden include emissions from other inputs to the process.

Whilst scarce information was found on the non-GHG emissions associated with hydrogen production from coal, more comprehensive evidence was found on the emissions from coal gasification to produce power (Skone et al., 2012) and due to the similarity of the process, these could be used to give an initial indication of potential levels of pollutant emissions. Both with and without CCS, the total non-GHG emissions are highest for NOx, SOx and PM, substantially lower for VOC and CO, and very low for lead, mercury and ammonia. However some species may pose a severe threat to human health or the environment, even at very low emission levels and so relative values must be treated cautiously.

Emissions (kg / MWh)	Plant Construction		Plant Operation		Installation/ Deinstallation		Total	
	Mass (kg)	kg CO_2e	Mass (kg)	kg CO_2e	Mass (kg)	kg CO_2e	Mass (kg)	kg CO_2e
CO_2	0.66	0.66	782.24	782.24	0.04	0.04	782.95	782.95
N_2O	1.55E-05	4.62E-03	3.42E-06	1.02E-03	1.05E-06	3.13E-04	2.00E-05	5.95E-03
CH_4	1.15E-03	2.87E-02	2.97E-03	7.41E-02	2.09E-05	5.23E-04	4.13E-03	1.03E-01
SF_6	4.57E-08	1.04E-03	2.87E-07	6.55E-03	6.57E-15	1.50E-10	3.33E-07	7.59E-03
Total GWP		0.70		782.33		0.04		783.06

Figure 3 Greenhouse gas emissions from coal gasification without CCS in kg / MWh plant electrical output (Skone et al. 2012)

Emissions (kg / MWh)	Plant Construction	Plant Operation	Installation/ Deinstallation	Total
Pb	4.5E-07	1.2E-05	9.5E-11	1.2E-05
Hg	2.9E-08	2.4E-06	1.3E-11	2.4E-06
NH_3	4.2E-07	1.4E-08	1.6E-06	2.0E-06
CO	2.5E-03	3.9E-04	1.7E-03	4.7E-03
NOx	1.3E-03	2.3E-01	6.3E-04	2.3E-01
SOx	1.8E-03	5.3E-02	2.7E-05	5.5E-02
VOC	5.3E-05	2.1E-05	1.7E-04	2.4E-04
PM	7.0E-04	3.0E-02	8.5E-05	3.1E-02

Figure 4 Air pollutant emissions from coal gasification without CCS in kg / MWh plant electrical output (Skone et al. 2012)

Emissions/ MWh	Plant Construction		Installation/ Deinstallation (I/D)		Plant Operation		CO_2 Pipeline I/D		Total	
	Mass (kg)	kg CO_2e	Mass (kg)	kg CO_2e	Mass (kg)	kg CO_2e	Mass (kg)	kg CO_2e	Mass (kg)	kg CO_2e
CO_2	1.01	1.01	0.05	0.05	102.71	102.71	0.03	0.03	103.80	103.80
N_2O	3.32E-05	9.89E-03	1.24E-06	3.71E-04	3.91E-06	1.17E-03	6.67E-07	1.99E-04	3.90E-05	1.16E-02
CH_4	1.49E-03	3.73E-02	2.48E-05	6.19E-04	3.40E-03	8.49E-02	1.33E-05	3.32E-04	4.93E-03	1.23E-01
SF_6	4.66E-08	1.06E-03	7.78E-15	1.77E-10	3.29E-07	7.50E-03	4.16E-15	9.50E-11	3.75E-07	8.56E-03
Total GWP		1.05		0.05		102.80		0.03		103.94

Figure 5 Greenhouse gas emissions from coal gasification with CCS in kg / MWh plant electrical output. I/D refers to installation / deinstallation (Skone et al. 2012)

Emissions (kg/ MWh)	Plant Construction	Plant Operation	Pipeline I/D	Plant I/D	Total
Pb	1.31E-06	1.38E-05	6.03E-11	1.13E-10	1.51E-05
Hg	6.17E-08	2.76E-06	8.21E-12	1.53E-11	2.82E-06
NH_3	4.22E-07	1.64E-08	9.95E-07	1.86E-06	3.29E-06
CO	5.12E-03	4.48E-04	1.08E-04	2.06E-03	7.74E-03
NO_X	1.92E-03	2.29E-01	3.13E-04	7.50E-04	2.32E-01
SO_X	2.83E-03	4.68E-02	7.27E-06	3.23E-05	4.97E-02
VOC	9.94E-05	2.46E-05	2.32E-05	1.98E-04	3.45E-04
PM	9.87E-04	3.43E-02	6.11E-05	1.00E-04	3.54E-02

Figure 6 Air pollutant emissions from coal gasification with CCS in kg / MWh plant electrical output. I/D refers to installation / deinstallation (Skone et al. 2012)

The level of CO_2 emitted is lower in the case with CCS than in the case without CCS because it is captured, but all other emissions (apart from SOx) are higher in the case with CCS. As discussed in the case of SMR, this difference is likely due to the energy requirement for CCS, and the need to construct additional equipment. However more research is needed to confirm that these conclusions apply to hydrogen production from coal gasification as well as power production from coal gasification.

Suggested further work: In order to obtain a narrower range of expected GHG emissions for hydrogen production from coal in the UK, and to obtain more comprehensive information on the non-GHG emissions species and emission rates, additional work would be required.

4.2.4 Biomass gasification

Biomass gasification is a commercial technology for heat and power production, but biomass gasification to hydrogen has not yet been proven at demonstration scale.

Non-GHG emissions: Miller et al. (2017) and Susmozas et al. (2013) report on the non-GHG emissions from biomass gasification, covering VOC, CO, NOx, particulates, SOx, H_2O, N_2 and O_2. Those species which contribute to global warming potential (CO_2, CH_4 and N_2O) are reported in Ramsden et al. (2013) and Edwards et al. (2014). These are summarised in Table 11. However, with little direct comparability between the sources, the data are not sufficient to allow any strong conclusions to be drawn. Miller suggests that the emissions from biomass gasification, across all pollutants considered, are several times higher than those from the production of the feedstock - meaning modelling the biomass gasification process itself will be an important consideration.

	Emissions from hydrogen production by biomass gasification (g/kWh_{H2})		
Emission	**Including hydrogen compression (Miller et al. 2017)**	**Including hydrogen liquefaction (Miller et al. 2017)**	**Excluding compression or liquefaction (figure / range given is from Susmozas et al.[a], 2013, Ramsden et al.[b], 2013, Edwards et al.[c], 2014)**
CO_2 (fossil)	87	199	51 [b]

CO_2 (biogenic)[9]	-	-	720 [b]
CH_4	0.238	0.557	0.0007-0.176 [b,c]
N_2O	0.049	0.052	0.0007 – 0.004 [b,c]
VOC	0.027	0.049	-
CO	0.107	0.225	-
NOx	0.192	0.359	0.27[a, figure applies specifically to NO2]
PM10	0.012	0.024	-
PM2.5	0.009	0.018	-
SOx	0.146	0.244	
O_2	-	-	571 [a]
N_2	-	-	3,402 [a]
H_2O	-	-	1245 [a]

Table 11 Summary of emissions from the production of hydrogen from biomass gasification without CCS. In all cases the feedstock is woody biomass, apart from Ramsden who assumes corn stover

No information was found on the likely rate of hydrogen leakage from biomass gasification plants, despite additional targeted searching.

Suggested further work: Currently, the data available on the likely emissions from hydrogen production by biomass gasification in the UK are not robust enough for policy-making. However, obtaining more reliable results relies on accurately defining the technology and biomass used, which may not be possible given the current early stage of development. Given there are no operating plants from which empirical data could be obtained even further work is unlikely to be able to provide a high level of accuracy on possible emissions.

4.3 Emissions from hydrogen transport

Transport via pipeline: Only five studies were identified quantifying the leakage rates from the transport of hydrogen in pipelines, likely because this concept has only recently begun to gain widespread interest. There were no detailed studies specific to the UK and the evidence concerning hydrogen leakage from pipelines is not therefore considered sufficient for making policy decisions in the UK. However, some useful findings were apparent which might help to inform the approach adopted.

The studies were found to fall into three broad categories:

1. *Whole system studies:* Studies which quantify hydrogen leakage rates from existing gas grids based on modelling of an entire network in a particular region and the application of theoretical principles relating to gas diffusion etc.;
2. *Future pathway studies:* Studies which model specific future hydrogen delivery pathways which apply and report on assumed leakage rates at different points in the system; and
3. *Test rig studies:* Reports and papers which describe empirical studies to ascertain hydrogen leakage rates from test-beds consisting of specific piping types.

[9] Conventionally biogenic CO_2 is not considered to be a 'greenhouse gas' as it does not represent a net CO_2 flow to the atmosphere. Therefore in studies which focus only on GHG emissions, point emissions from the plant of biogenic CO_2 may not be considered or reported in the source, even though without CCS these are likely to be large.

At a high level it can be said that hydrogen leakage rates are likely to be higher, all else being equal, than for natural gas owing to the small molecule size of hydrogen. A single study (Melaina et al., 2013) reported that the rate of hydrogen leakage would be around three times higher than the rate of natural gas leakage in a steel pipe network, based on a study from the Gas Technology Institute. However, such a conclusion is not necessarily applicable to plastic pipes, as the mechanism for leakage varies between iron or steel mains and those employing plastics such as polyethylene or PVC, with gas escape in the former being around joints and equipment such as valves, and in the latter predominantly through permeation. Moreover, evidence on natural gas emissions from the UK grid (Mitchell et al. (1990), Derwent et al. (2017)) suggests current leakage rates may be underreported, and after the completion of the Iron Mains Replacement Programme leakage rates are likely to differ. Further work may be needed to explore this.

The majority of the studies which were reviewed focussed on countries outside the UK. Given the wide variability in the properties of natural gas grids around the world (Figure 7), conclusions from these non-UK studies should therefore not be extrapolated to the UK gas grid.

Country	**D**	**USA**	**Japan**	**Arg**	**Can.**	**UK**	**F**	**I**	**NL**
response of grid owners in % of national grid length	100%	8% (est.)	67%	36%	31%	95%	100%	35%	29%
Total grid length considered in questionnaire (km)	293,200	70,740	147,170	35,080	26,090	270,000	143,510	43,452	24,238
P< 100 mbar			69%	2%	7%	93%	16%	61%	78%
100mbar<P<2 bar			28%	80%	0%	0	0%	14%	9%
2 bar<P< 5 bar	74% < 4 bar	97 % < 5 bar	0	10%	80%	0	79%	24%	5%
P> 5 bar	26 % > 4 bar	3%	3%	8%	13%	7%	4%	1%	8%
Type	A	A	B	B	A	B	A	B	B

Figure 7 Comparison of gas networks in several developed countries in terms of network length and operating pressures (Ref. Haines et al., 2003)[10]

A study of the Netherlands gas network and reported in Melaina et al. (2013), estimates hydrogen leakage rates through permeation to be in the order of 0.0005% of total hydrogen transported, with a 17% hydrogen blend, based on theoretical permeation rates. By contrast, Ramsden et al. (2013) estimates the hydrogen leakage rate in the US to be 0.77%[11], based on previous published literature. The US gas grid contains a mix of PVC and iron mains pipes. However, published research[12] from Alvarez et al (2018) suggests US grid leakage could be underestimated by up to 60%. Getting reliable figures for gas grid leakage rates is evidently challenging, and represents a potential risk for any future work on decarbonisation of the gas grid.

[10] D – Germany, F – France, I – Italy, NL – The Netherlands. Type A – customer supply at 2 – 5bar, Type B – distribution at 100mBar or lower)
[11] This seems to be based on a 100% hydrogen pipeline, although this is not explicitly stated in the paper.
[12] Alvarez et al, *Assessment of methane emissions from the U.S. oil and gas supply chain* http://science.sciencemag.org/content/early/2018/06/20/science.aar7204?rss=1 This study was not formally assessed as part of this literature survey, as it was published after the literature assessment had been completed.

Two interesting results emerged from more than one of the studies (Melaina et al. 2013, Haines et al.2013) that was reviewed and these would merit further investigation.

The first is that leakage rates measured empirically in studies of plastic pipework were found to be lower than would be predicted by theoretical permeabilities. While the extent of the deviation is not quantified, the finding serves to highlight the importance of both experimental as well as theoretical studies.

The second is that when hydrogen is blended with natural gas, the proportion of natural gas leakage is lower than the proportion mix and relative diffusion rates would predict. For example, reported results from the NaturalHy project (Melaina et al. 2013) suggest that with a 10% hydrogen blend, leakage of NG is roughly half what would be predicted using American Gas Association coefficients (see Figure 8 below). This was not confirmed empirically by other studies identified in this report and further analysis would be merited to confirm the finding.

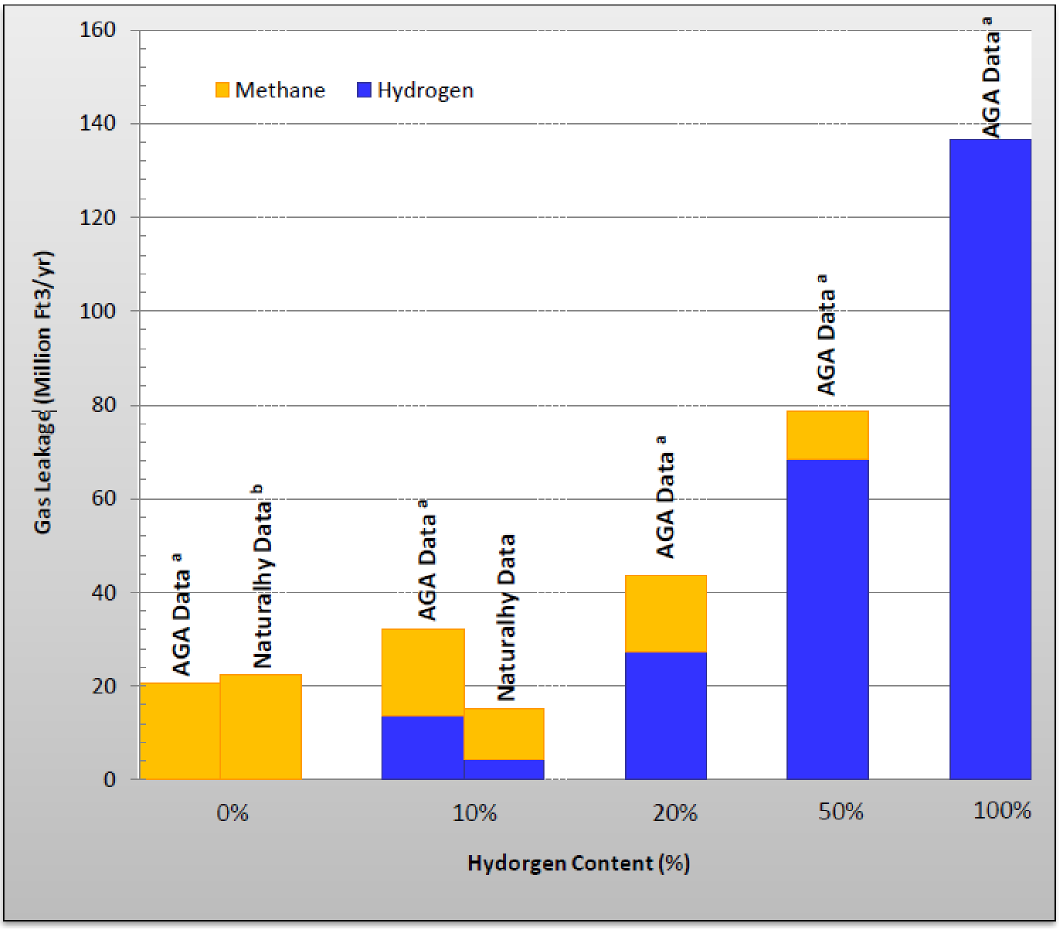

Figure 8 Gas leakage rates from pipes at varying blends of hydrogen in natural gas (Melaina et al., 2013)

Sadler et al. (2016), Edwards et al. (2014) and Ramsden et al. (2013) all report on the GHG emissions from hydrogen transport via pipeline. These are likely to be small compared to the rest of the hydrogen value chain, as GHG emissions will be mostly due to electricity consumption by equipment such as compressors. GHG emissions from hydrogen transport by pipeline vary depending on the pressure at which the gas is transported, so this should be clearly specified in any future studies. These would also be affected by changes to the electricity grid mix.

Transport via truck or ship: In contrast to the findings for pipelines, it seems reasonable to assume that leakage rates from transport by truck would not be geographically specific given the similarities in truck design that exist, and results estimated for other countries would be perhaps be more relevant to the UK. Ramsden et al. (2013) quantifies leakage from truck transport in the US at between 1% for compressed gas transport and 2.3% for liquid hydrogen transport, but with no other sources to support these figures, they are not reliable enough for basing policy decisions on.

Edwards et al. (2014) states that shipping of liquid H_2 by sea (10,000km) could result in GHG emissions of 26.28 $gCO_2eq./kWh_{H2}$ while emissions from "conditioning and distribution", which includes transport over 500km by road, are reported as 15.12 $gCO_2eq./kWh_{H2}$. Ramsden et al. (2013) meanwhile reports emissions of 27.81 $gCO_2eq./kWh_{H2}$ for transport of gaseous hydrogen 100km by road, including compression and storage. These are of a similar order of magnitude as $CO_{2eq.}$ emissions from upstream gas or coal extraction, and substantially lower than unabated hydrogen production by coal or SMR. Emissions from hydrogen transport are dependent on the mode of transport and distance transported but will also be affected by what is considered to be "in scope" within the study.

Suggested further work: To obtain estimates of leakage rates specific to the UK gas network a model of the UK gas network could be used to explore the impact of different operating regimes (e.g. varying hydrogen blends) both with the current infrastructure and in light of the iron mains replacement. Empirical evidence would be required to confirm the accuracy of modelling outputs. Measurement of current natural gas leakage rates could be made on parts of the grid where the Iron Mains Replacement Programme has been completed and hydrogen leakage rates could be measured in current or future hydrogen projects, such as HyDeploy.

4.4 Emissions from end-use of hydrogen

GHG emissions: The combustion of hydrogen releases no direct greenhouse gases.

Non-GHG emissions: The evidence base relating to non-GHG emissions from end-use in heating applications is almost non-existent. Cellek et al (2018) attempts to quantify the non-GHG emissions from an innovative hydrogen boiler design which suggests there is potential for up to six times higher point NOx emissions compared with natural gas. Sadler et al. (2016) confirms qualitatively the potential for higher NOx emissions but argues that technologies such as catalytic combustors can reduce this risk, with low temperature catalytic combustion producing zero NOx and high temperature catalytic combustion producing "low" NOx, although this is not quantified and the commercial implications are unclear.

Hydrogen leakage at the point of end-use was not discussed in any of the sources reviewed.

NOx emissions from such fuel cell systems are likely to be low compared with natural gas boilers.

Suggested further work: Further empirical research would be needed to confirm likely levels of non-GHG emissions from hydrogen combustion and use in fuel cells.

Study	CO_2	NOx	Particulate Matter	Other	H_2 Leakage
Leeds Citygate (Sadler et al., 2016		C: High (unless mitigated) HTCC: Always low LTCC: Zero HFC: Very low			
HyHouse Study: Safety issues surrounding hydrogen as an energy storage vector (Crowther et al., 2015)					H_2 leakage relative to NG is lower than predicted by theory
Energy, economic and environmental analysis on RET-hydrogen systems in residential buildings (Beccali et al., 2008)		Gas boiler (NG): 1.896 g/m³ HFC: 0.676 g/kg$_{hydrogen}$ NGFC: 0.195 g/m³ NG	Gas boiler: 0.024 g/m3 NG NGFC: 0.192 g/m3 NG	**<u>CO</u>** Gas boiler: 0.474 g/m³ NG NGFC: 0.351 g/m³ NG **<u>Volatile organic compounds</u>** Gas boiler: 0.474 g/m³ NG NGFC: 0.120 g/m³ NG **<u>SOx</u>** Gas boiler: 0.0079 g/m³ NG HFC: 0.676 g/kg$_{hydrogen}$ NGFC: 0.195 g/m³ NG	
Impact of micro-CHP systems on domestic sector CO_2 emissions (Peacock et al., 2005)	Annual emissions compared to business-as-usual Stirling engine (1): +3% Stirling engine (2): -10% Stirling engine (3): -9% HFC (1kW): -16% HFC (3kW): - 40%				
Investigations on performance and emission characteristics of an industrial low swirl burner while burning natural gas, methane, hydrogen-enriched natural gas and hydrogen as fuels (Cellek et al., 2018)		Increase compared to business-as-usual of different H_2/NG blends 25%: +92.81% 50%: +219.72% 75%: +360% 100%: +659.30%			

Table 12 Summary of emissions from hydrogen end-use

C = Combustion; HTCC = High temperature catalytic combustion; LTCC = Low temperature catalytic conversion; HFC = Hydrogen fuel cell; NGFC = Natural gas fuel cell; RET = Renewable Energy Thermal

Stirling engine scenarios: 1) unrestricted thermal surplus, 2) restricted thermal surplus and 3) restricted thermal surplus and part load capability

Appendix A Shortlist of sources

Title of publication	Publication date	Author name(s)
H21 Leeds CityGate Project Report	2016	Sadler, D. et al.
Biohydrogen: Production of hydrogen by gasification of waste	2017	Cairns-Terry, M.
Hydrogen Pathways Updated Cost, Well-to-Wheels Energy Use, and Emissions for the Current Technology Status of Ten Hydrogen Production, Delivery and Distribution Scenarios	2013	Ramsden, T., Ruth, M., Diakov, V., Laffen, M., Timbario, T.A.
HyHouse Study: Safety issues surrounding hydrogen as an energy storage vector	2015	Crowther, M., Orr, G., Thomas, J., Stephens, G., Summerfield, I.
White Paper 1: Methane & CO2 emissions from the natural gas supply chain	2015	Balcombe, P., Anderson, K., Speirs, J., Brandon, N., Hawkes, A.
Life cycle assessment of renewable hydrogen production via wind/electrolysis	2004	Spath, P.L., Mann, M.K.
The Development of Lifecycle Data for Hydrogen Fuel Production and Delivery	2017	Miller, M
Blending Hydrogen into Natural Gas Pipeline Networks: A Review of Key Issues	2013	Melaina, M.W., Antonia, O., Penev, M.
The estimation of fugitive gas emissions from hydrogen production by natural gas steam reforming	2017	Alhamdani, Y.A., Hassim, M.H., Ng, R.T.L., Hurme, M.
Life Cycle Assessment of Hydrogen Production via Natural Gas Steam Reforming	2001	Spath, P.L., Mann, M.K.
Comparison of Life Cycle Greenhouse Gases from Natural Gas Pathways for Light-Duty Vehicles	2015	Tong, F., Jaramillo, P., Azvedo, I.M.L.
Hydrogen Production from Fossil Fuels: Life Cycle Assessment of Technologies with Low Greenhouse Gas Emissions	2011	Dufour, J., Serrano, D.P., Galvez, J.L., Moreno, J.m Gonzalez, A.
Life Cycle Assessment and Water Footprint of Hydrogen Production Methods: From Conventional to Emerging Technologies	2017	Mehmeti, A., Angelis-Dimakis, A., Arampatzis, G., McPhail, S.J., Ulgiati, S.
Desk study on the development of a hydrogen-fired applicant supply chain	2016	Dorrington, M., Lewitt, M., Summerfield, I., Robson, P., Howes, J.
Harmonised life-cycle global warming impact of renewable hydrogen	2017	Valente, A., Iribarren, D., Dufour, J.
Well-to-Tank Report (version 4.a)	2014	Edwards, R., Larive, J-F., Rickdeard, D., Weindorf, W.
Ecoinvent	2017	
Life-cycle assessment of a hydrogen-based uninterruptible power supply system using renewable energy	2014	Mori, M., Jenterle, M., Mrzljak, T., Drobnic, B.
Study on actual GHG data for diesel, petrol, kerosene and natural gas	2015	DG ENER
Comparative assessment of hydrogen production methods from renewable and non-renewable sources	2014	C. D. Acar, I. Dincer

Towards clean and sustainable distributed energy system: the potential of integrated PEMFC-CHP	2016	Aleknaviciute, I.; Karayiannis, T. G.; Collins, M. W.; Xanthos, C.
Energy, economic and environmental analysis on RET-hydrogen systems in residential buildings	2008	Beccali, M.; Brunone, S.; Cellura, M.; Franzitta, V.
Life cycle assessment of various hydrogen production methods	2012	Cetinkaya, E.; Dincer, I.; Naterer, G. F.
Review and evaluation of hydrogen production methods for better sustainability	2015	Dincer, I.; Acar, C.
Life cycle assessment of alternatives for hydrogen production from renewable and fossil sources	2012	Dufour, J.; Serrano, D. P.; Galvez, J. L.; Gonzalez, A.; Soria, E.; Fierro, J. L. G.
Economic and environmental assessment of residential micro combined heat and power system application in Japan	2016	H. Ito
Eco-efficiency of H(2) and fuel cell buses	2011	Lee, J. Y.; Cha, K. H.; Lim, T. W.; Hur, T.
The use of natural gas pipeline network with different energy carriers	2015	Ma, L. L.; Spataru, C.
Techno-economic analysis and life cycle assessment of hydrogen production from natural gas using current and emerging technologies	2017	Salkuyeh, Y. K.; Saville, B. A.; MacLean, H. L.
Life-cycle performance of indirect biomass gasification as a green alternative to steam methane reforming for hydrogen production	2013	Susmozas, A.; Iribarren, D.; Dufour, J.
Life cycle assessment of hydrogen production from underground coal gasification	2015	Verma, A.; Kumar, A.
Comparing air quality impacts of hydrogen and gasoline	2008	Wang, G. H.; Ogden, J. M.; Sperling, D.
Impact of micro-CHP systems on domestic sector CO2 emissions	2005	Peacock, A.D., Newborough, M.
Investigations on performance and emission characteristics of an industrial low swirl burner while burning natural gas, methane, hydrogen-enriched natural gas and hydrogen as fuels	2018	Cellek, Mehmet Salih; Pınarbaşı, Ali
Solid and gaseous bioenergy pathways: input values and GHG emissions: Calculated according to methodology set in COM(2016) 767: Version 2	2017	Giuntoli, J., Agostini, A., Edwards, R., Marelli, L.
Creation of unit process data for life cycle assessment of steam methane reforming and petroleum refining	2017	Young, B., Morelli, B., Hawkins, T.R.,

Appendix B Quality assessment criteria

Quality Assessment Criteria	Maximum Score	Score
Are the rationale (1 point) and research questions (1 point) clear and justified?	2	
Does the document acknowledge resource contributions (1 point) and possible conflicts of interest (1 point)?	2	
Are the methods used suitable for the aims of the study (1 point)?	1	
Has the document been peer reviewed or independently verified by one (1 point) or more reputable experts (2 points)?	2	
Do the conclusions match the data presented (1 point)?	1	
Does the author / publishing organisation have a track record in the area? (1 point)?	1	
TOTAL ***(documents must score ≥6/9 to pass)***	**9**	

Appendix C Long-list of sources

Title of publication	Publication date	Author name(s)
H21 Leeds CityGate Project Report	2016	Sadler, D. et al.
HyDeploy Project, first Project Progress Report	2017	Cadent
Gas NIC submission from National Grid Gas Distribution - HyDeploy	2016	Lewis, A.
H21 Network Innovation Competition Submission	2017	Sadler, D. et al.
Biohydrogen: Production of hydrogen by gasification of waste	2017	Cairns-Terry, M.
Hydrogen Pathways Updated Cost, Well-to-Wheels Energy Use, and Emissions for the Current Technology Status of Ten Hydrogen Production, Delivery and Distribution Scenarios	2013	Ramsden, T., Ruth, M., Diakov, V., Laffen, M., Timbario, T.A.
Greenlysis Final Technical Report	2013	Serra, A.G. et al
Commercial Scale Feasibility of Clean Hydrogen	2017	Commercial scale feasibiliyt of clean hydrogen
Techno-economic evaluation of SMR based standalong (Merchant) hydrogen plant with CCS	2017	Collodi, G., Azzaro, G., Ferrari, N.
Hydrogen and Fuel Cells: Opportunities for Growth A roadmap for the UK	2016	Hart, D., Howes, J., Madden, B., Boyd, E.
HyHouse Study: Safety issues surrounding hydrogen as an energy storage vector	2015	Crowther, M., Orr, G., Thomas, J., Stephens, G., Summerfield, I.
The Liverpool-Manchester Hydrogen Cluster: A low cost, deliverable project	2017	
White Paper 1: Methane & CO2 emissions from the natural gas supply chain	2015	Balcombe, P., Anderson, K., Speirs, J., Brandon, N., Hawkes, A.
White Paper 3 -A Greener Gas Grid: What Are The Options?	2017	
Life cycle assessment of renewable hydrogen production via wind/electrolysis	2004	Spath, P.L., Mann, M.K.
Economic assessment of selected hydrogen production methods: A review	2017	Wang, Y., Zhang, S.
Life-Cycle Analysis of Water Consumption for Hydrogen Production Pathways	2014	Elgowainy, A., Wu, M., Lampert, D., Cai, H., Han, J., Wang, M.
Life cycle assessment of hydrogen production via electrolysis - A review	2014	Bhandari, R., Trudewind, C.A., Zapp, P.
Life Cycle Assessment of improved high pressure alkaline electrolysis	2015	Koj, J.C., Schreiber, A., Zapp, P., Marcuello, P.
Assessing the Life-Cycle Performance of Hydrogen Production via Biofuel Reforming in Europe	2015	Susmozas, A., Iribarren, D., Dufour, J.
Life Cycle Analysis of Hydrogen Production from Non-Fossil Sources	2016	Dai, Q., Elgowainy, A., Kelly, J., Han, J., Wang, M.
Comparative impact assessment study of various hydrogen production methods in terms of emissions	2015	Suleman, F. Dincer, I., Agelin-Chaab, M.
The Development of Lifecycle Data for Hydrogen Fuel Production and Delivery	2017	Miller, M
Comparative impact assessment study of various hydrogen production methods in terms of emissions	2003	Gastec
Blending Hydrogen into Natural Gas Pipeline Networks: A Review of Key Issues	2013	Melaina, M.W., Antonia, O., Penev, M.

The estimation of fugitive gas emissions from hydrogen production by natural gas steam reforming	2017	Alhamdani, Y.A., Hassim, M.H., Ng, R.T.L., Hurme, M.
Methane cracking as a bridge technology to the hydrogen economy	2017	Weger, L., Abanades, A., Butler, T.
Life cycle greenhouse emissions of compressed natural gas–hydrogen mixtures for transportation in Argentina	2010	Martinez, P., Dawidowski, L., Gomez, D., Pasquevich, D.
Life-Cycle Analysis of Greenhouse Gas Emissions for Hydrogen Fuel Production in the United States from LNG and Coal	2005	Ruether, J., Ramezan, M., Grol, E.
SHOULD WE ADD HYDROGEN TO THE NATURAL GAS GRID TO REDUCE CO2-EMISSIONS? (CONSEQUENCES FOR GAS UTILIZATION EQUIPMENT	2006	Slim, B.K. et al.
Life Cycle Assessment of Hydrogen Production via Natural Gas Steam Reforming	2001	Spath, P.L., Mann, M.K.
Life Cycle Assessment of Natural gas-based Chemical Looping for Hydrogen Production	2014	Petrescu, L., Muller, C.R., Cormos, C-C.
Comparison of Life Cycle Greenhouse Gases from Natural Gas Pathways for Light-Duty Vehicles	2015	Tong, F., Jaramillo, P., Azvedo, I.M.L.
Comparative life cycle assessment of hydrogen pathways from fossil sources in China	2016	Dong, J., Liu, X., Xu, X., Zhang, S.
Hydrogen Production via Natural Gas Reforming Process – A Life Cycle Assessment Approach	2012	Ozturk, M., Ozek, N.
Hydrogen Production from Fossil Fuels: Life Cycle Assessment of Technologies with Low Greenhouse Gas Emissions	2011	Dufour, J., Serrano, D.P., Galvez, J.L., Moreno, J.m Gonzalez, A.
Life Cycle Assessment of Simulated Hydrogen Production by Methane Steam Reforming	2017	Amran, U.I., Ahmad, A., Othman, M.R.
Hydrogen production and distribution	2007	
Potential Role of Hydrogen in the UK Energy System	2016	
Developing hydrogen fueling infrastructure for fuel cell vehicles: A status update	2017	Isenstadt, A., Lutsey, N.
A HYDROGEN FUTURE? An Economic and Environmental Assessment of Hydrogen Production Pathways	2005	Herzog, A., Tatsutani, M.
Analysis of CO2 Emissions, Reducstion, and Capture for Large-Scale Hydrogen Production Plants	2010	Bonaquist, D.
Well to wheel analysis of low carbon alternatives for road traffic	2015	Ramachandran, S., Stimming, U.
Conversion of the UK gas system to transport hydrogen	2013	Dodds, P., Demoullin, S.
Hydrogen Pathways: Cost, Well-to-Wheels Energy Use, and Emissions for the Current Technology Status of Seven Hydrogen Production, Delivery, and Distribution Scenarios	2009	Ruth, M., Laffen, M., Timbario, T.A.
A review of hydrogen delivery technologies for energy system models	2012	Dodds, P., McDowell, W.
Overview of Interstate Hydrogen Pipeline Systems	2007	Gilette, J.L., Kolpa, R.L.
Analysis of hazard area associated with hydrogen gas transmission pipelines	2005	Jo, Y-D., Park, K.S. Ko, J.W. and Ahn, B.J.

Hydrogen from renewables	2009	Haeseldonckx, D., D'haeseleer, W.,
Life Cycle Assessment and Water Footprint of Hydrogen Production Methods: From Conventional to Emerging Technologies	2017	Mehmeti, A., Angelis-Dimakis, A., Arampatzis, G., McPhail, S.J., Ulgiati, S.
Desk study on the development of a hydrogen-fired applicant supply chain	2016	Dorrington, M., Lewitt, M., Summerfield, I., Robson, P., Howes, J.
Harmonised life-cycle global warming impact of renewable hydrogen	2017	Valente, A., Iribarren, D., Dufour, J.
Well-to-Tank Report (version 4.a)	2014	Edwards, R., Larive, J-F., Rickdeard, D., Weindorf, W.
Development of a Life Cycle Inventory of Water Consumption Associated with the Production of Transportation Fuels	2014	Lampert, D., Cai, H., Wang, Z., Keisman, J., Wu, M., Han, J., Dunn, J., Frank, E., Sullivan, J., Elgowainy, A., Wang, M.
GREET life cycle analysis tool	2017	
Ecoinvent	2017	
GHGenius 4.03	2014	
Well to tank Technology Pathways and Carbon Balance	2009	Prieur, A., Favreau, D., Vinot, S.
Comparison of biohydrogen production processes	2008	Manish, S. & Banerjee, R.
Life cycle assessment of the production of hydrogen and transportation fuels from corn stover via fast pyrolysis	2013	Zhang, Y., Hu, G., Brown, R.C.
Life cycle assessment of transportation fuels from biomass pyrolysis	2012	Iribarren D, Peters J F and Dufour J
Life-cycle assessment of a hydrogen-based uninterruptible power supply system using renewable energy	2014	Mori, M., Jenterle, M., Mrzljak, T., Drobnic, B.
Life cycle assessment of hydrogen fuel production processes	2004	Koroneos, C., Dompros, A., Roumbas, G. Moussiopoulos, N.
Final Report: Värnamo Demonstration Programme	2008	Stahl, K., Neergaard, M., Nieminen, J.
Integrated Design for Demonstration of Efficient Liquefaction of Hydrogen (IDEALHY)	2013	Mortimer, N.D., Hatto, C., Mwabonje, O., Rix, J.H.R.
HyTEC Final Life Cycle Assessment Report	2015	Bauimann, M., Vega, L.F., Blejan, G., Ruiz, P.
Potential Greenhouse Gas Emissions Associated with Shale Gas Extraction and Use	2013	MacKay, D., Stone, T.
Co-production of hydrogen, electricity and CO2 from coal with commercially ready technology. Part A: Performance and emissions	2005	Chiesa, P., Consonni, S.,. Kreutz, T., Williamsn, R.
Hydrogen-based energy conversion	2014	Decourt, B., Lajoie, B., Debarre, R., Soupa, O.
Scenarios for deployment of hydrogen in contributing to meeting carbon budgets and the 2050 targetes	2015	Hart, D., Howes, J., Lehner, F., Dodds, P., Highes, N., Fais, B., Sabio, N., Crowther, M.
Life cycle assessment of a large-scale centrifugal compressor: A case study in China	2016	Peng, S., Li, T., Dong, M., Shi, J., Zhang, H.
Study on actual GHG data for diesel, petrol, kerosene and natural gas	2015	
Comparative assessment of hydrogen production methods from renewable and non-renewable sources	2014	C. D. Acar, I. Dincer
Comparative life cycle assessment of hydrogen fuel cell passenger vehicles in different Canadian provinces	2015	P. K. Ahmadi, E. Kjeang
Co-gasification of coal and wood in a dual fluidized bed gasifier	2011	I. P. Aigner, C.; Pfeifer C.; Hofbauer, H.

Towards clean and sustainable distributed energy system: the potential of integrated PEMFC-CHP	2016	Aleknaviciute, I.; Karayiannis, T. G.; Collins, M. W.; Xanthos, C.
Integration of renewable energy sources into combined cycle power plants through electrolysis generated hydrogen in a new designed energy hub	2016	K. F. AlRafea, M.; Elkamel, A.; Hajimiragha, A.
Presenting the implementation of power-to-gas to an oil refinery as a way to reduce carbon intensity of petroleum fuels	2017	Al-Subaie, A.; Maroufmashat, A.; Elkamel, A.; Fowler, M.
Energy, economic and environmental analysis on RET-hydrogen systems in residential buildings	2008	Beccali, M.; Brunone, S.; Cellura, M.; Franzitta, V.
Using non-parametric statistics to identify the best pathway for supplying hydrogen as a road transport fuel	2011	Bishop, J. D. K.; Axon, C. J.; Banister, D.; Bonilla, D.; Tran, M.; McCulloch, M. D.
Environmental life cycle feasibility assessment of hydrogen as an automotive fuel in Western Australia	2013	Biswas, W. K.; Thompson, B. C.; Islam, M. N.
Life cycle assessment of various hydrogen production methods	2012	Cetinkaya, E.; Dincer, I.; Naterer, G. F.
Exergy analysis and CO2 emission evaluation for steam methane reforming	2012	Chen, B.; Liao, Z. W.; Wang, J. D.; Yu, H. J.; Yang, Y. R.
Evaluation of energy integration aspects for IGCC-based hydrogen and electricity co-production with carbon capture and storage	2010	C. C. Cormos
Hydrogen utilization in various transportation modes with emissions comparisons for Ontario, Canada	2012	Cuda, P.; Dincer, I.; Naterer, G. F.
Electricity systems with near-zero emissions of CO2 based on wind energy and coal gasification with CCS and hydrogen storage	2009	J. Davison
Novel quasi-autothermal hydrogen production process in a fixed-bed using a chemical looping approach: A numerical study	2017	Diglio, G.; Bareschino, P.; Mancusi, E.; Pepe, F.
Review and evaluation of hydrogen production methods for better sustainability	2015	Dincer, I.; Acar, C.
Comparative life cycle assessment of three biohydrogen pathways	2011	Djomo, S. N.; Blumberga, D.
Life cycle assessment of alternatives for hydrogen production from renewable and fossil sources	2012	Dufour, J.; Serrano, D. P.; Galvez, J. L.; Gonzalez, A.; Soria, E.; Fierro, J. L. G.
Exergy analysis of underground coal gasification with simultaneous storage of carbon dioxide	2012	Eftekhari, A. A.; Van der Kooi, H.; Bruining, H.
Energy consumption and CO2 emissions of potato peel and sugarcane biohydrogen production pathways, applied to Portuguese road transportation	2011	Ferreira, A. F.; Ribau, J. P.; Silva, C. M.
Stand-alone and biorefinery pathways to produce hydrogen through gasification and dark fermentation using Pinus Patula	2017	Garcia, C. A.; Betancourt, R.; Cardona, C. A.
Environmental assessment of hydrogen production based on Pinus patula plantations in Colombia	2017	Garcia, C. A.; Morales, M.; Quintero, J.; Aroca, G.; Cardona, C. A.
Life cycle assessment of wind-based hydrogen production in Western Canada	2016	Ghandehariun, S.; Kumar, A.
Life cycle assessment of hydrogen production from a high temperature electrolysis process coupled to a high temperature gas nuclear reactor	2015	Giraldi, M. R.; Francois, J. L.; Martin-del-Campo, C.

Power-to-gas plants and gas turbines for improved wind energy dispatchability: Energy and economic assessment	2015	Guandalini, G.; Campanari, S.; Romano, M. C.
Thermodynamic investigation and environment impact assessment of hydrogen production from steam reforming of poultry tallow	2014	N. Hajjaji
Comparative assessment of greenhouse gas mitigation of hydrogen passenger trains	2008	Haseli, Y.; Naterer, G. F.; Dincer, I.
Economic analysis of hydrogen production from wastewater and wood for municipal bus system	2013	Hatch, C.; Center, A.; Feitelberg, A. S.; Fisher, E. M.; Mutolo, P. F.
Life-cycle analysis of greenhouse gas emission and energy efficiency of hydrogen fuel cell scooters	2010	Hwang, J. J.; Chang, W. R.
Lifecycle performance assessment of fuel cell/battery electric vehicles	2013	Hwang, J. J.; Kuo, J. K.; Wu, W.; Chang, W. R.; Lin, C. H.; Wang, S. E.
Economic and environmental assessment of residential micro combined heat and power system application in Japan	2016	H. Ito
Development of net energy ratio and emission factor for biohydrogen production pathways	2011	Kabir, M. R.; Kumar, A.
Life cycle assessment of hydrogen production from biomass gasification systems	2012	Kalinci, Y.; Hepbasli, A.; Dincer, I.
Performance assessment of hydrogen production from a solar-assisted biomass gasification system	2013	Kalinci, Y.; Hepbasli, A.; Dincer, I.
Eco-efficiency of H(2) and fuel cell buses	2011	Lee, J. Y.; Cha, K. H.; Lim, T. W.; Hur, T.
A study on the environmental aspects of hydrogen pathways in Korea	2009	Lee, J. Y.; Yu, M. S.; Cha, K. H.; Lee, S. Y.; Lim, T. W.; Hur, T.
Updated hydrogen production costs and parities for conventional and renewable technologies	2010	Lemus, R. G.; Duart, J. M. M.
A comparative assessment of battery and fuel cell electric vehicles using a well-to-wheel analysis	2016	Li, M. Y.; Zhang, X. W.; Li, G. J.
Energy supply infrastructure LCA model for electric and hydrogen transportation systems	2013	Lucas, A.; Neto, R. C.; Silva, C. A.
The use of natural gas pipeline network with different energy carriers	2015	Ma, L. L.; Spataru, C.
Ecological analysis of hydrogen production via biogas steam reforming from cassava flour processing wastewater	2017	Madeira, J. G. F.; Boloy, R. A. M.; Delgado, A. R. S.; Lima, F. R.; Coutinho, E. R.; Pereira, R. D.
Life cycle assessment of hydrogen production from biomass gasification. Evaluation of different Spanish feedstocks	2013	Moreno, J.; Dufour, J.
Hydrogen production from wind energy in Western Canada for upgrading bitumen from oil sands	2011	Olateju, B.; Kumar, A.
Assessing Uncertainties of Well-To-Tank Greenhouse Gas Emissions from Hydrogen Supply Chains	2017	Ozawa, A.; Inoue, M.; Kitagawa, N.; Muramatsu, R.; Anzai, Y.; Genchi, Y.; Kudoh, Y.
Life cycle assessment of H-2 generation with high temperature electrolysis	2013	Patyk, A.; Bachmann, T. M.; Brisse, A.
Life cycle analysis of hydrogen - A well-to-wheels analysis for Portugal	2013	Pereira, S. R.; Coelho, M. C.
Evaluation of hydrogen production methods using the Analytic Hierarchy Process	2009	Pilavachi, P. A.; Chatzipanagi, A. I.; Spyropoulou, A. I.

Techno-economic analysis and life cycle assessment of hydrogen production from natural gas using current and emerging technologies	2017	Salkuyeh, Y. K.; Saville, B. A.; MacLean, H. L.
Demonstration of a novel assessment methodology for hydrogen infrastructure deployment	2009	Stephens-Romero, S.; Samuelsen, G. S.
Life-cycle performance of indirect biomass gasification as a green alternative to steam methane reforming for hydrogen production	2013	Susmozas, A.; Iribarren, D.; Dufour, J.
Cost-benefit analysis of different hydrogen production technologies using AHP and Fuzzy AHP	2014	Thengane, S. K.; Hoadley, A.; Bhattacharya, S.; Mitra, S.; Bandyopadhyay, S.
Potential for greenhouse gas emission reductions using surplus electricity in hydrogen, methane and methanol production via electrolysis	2017	Uusitalo, V.; Vaisanen, S.; Inkeri, E.; Soukka, R.
Hydrogen Use in an Urban District: Energy and Environmental Comparisons	2010	Vellini, M.; Tonziello, J.
Life cycle assessment of hydrogen production from underground coal gasification	2015	Verma, A.; Kumar, A.
Comparative life cycle assessment of power-to-gas generation of hydrogen with a dynamic emissions factor for fuel cell vehicles	2015	Walker, S. B.; Fowler, M.; Ahmadi, L.
Comparing air quality impacts of hydrogen and gasoline	2008	Wang, G. H.; Ogden, J. M.; Sperling, D.
Life cycle assessment of hydrogen supply chain with special attention on hydrogen refuelling stations	2012	Wulf, C.; Kaltschmitt, M.
Life Cycle Assessment of Power-to-Gas: Approaches, system variations and their environmental implications	2017	Zhang, X. J.; Bauer, C.; Mutel, C. L.; Volkart, K.
Development and environmental impact of hydrogen supply chain in Japan: Assessment by the CGE-LCA method in Japan with a discussion of the importance of biohydrogen	2014	Lee, D. H.
Impact of micro-CHP systems on domestic sector CO2 emissions	2005	Peacock, A.D., Newborough, M.
Investigations on performance and emission characteristics of an industrial low swirl burner while burning natural gas, methane, hydrogen-enriched natural gas and hydrogen as fuels	2018	Cellek, Mehmet Salih; Pınarbaşı, Ali
DOE H2A Production Analysis	2015	
Appraisal of Domestic Hydrogen Appliances	2018	
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