Environmental impacts of alternative fuels

Chief Scientist's Group research report

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Environment Agency

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Dr Robert Bradburne
Chief Scientist

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Executive summary

The United Kingdom (UK) has a legally binding target to reduce its greenhouse gas (GHG) emissions to net zero by 2050. “Alternative” fuels are expected to play a crucial role in achieving this target in the transport and industrial sectors. In the context of this report, alternative fuels refer to fuels that can be used as substitutes for conventional fossil fuels.

It is likely that new alternative fuel production and storage facilities will fall under the Environment Agency’s regulatory remit. Furthermore, responses to incidents such as fires, spills and leaks may need to use different methods for new fuels compared to conventional fossil fuels.

This study aimed to improve the evidence base available to the Environment Agency by identifying and reviewing the key alternative fuels and production pathways likely to be used in the UK by 2050, evaluating their environmental impacts and examining their incident management needs. It should be noted, however, that operators are ultimately responsible for gathering the evidence and demonstrating that their installations use sufficient measures to protect both people and the environment.

Ten alternative fuels were selected for analysis in this study:

- Biomethane via gasification
- e-Methane
- Fischer-Tropsch hydroprocessed synthesised paraffinic kerosene (FT-SPK)
- Synthesised kerosene with aromatics derived by alkylation of light aromatics from non-petroleum sources (FT-SKA)
- Alcohol to jet synthetic paraffinic kerosene (AtJ-SPK)
- Synthetic Paraffinic Kerosene with Aromatics (AtJ-SKA)
- Sustainable Aviation Fuel or diesel via pyrolysis
- Sustainable Aviation Fuel or diesel via hydrothermal liquefaction
- e-Diesel
- Green Ammonia

These pathways were selected in agreement with the Environment Agency at the inception of this study. The selected pathways are those that are more mature; that is, they have a higher technology readiness level (TRL) and are more likely to be deployed in the UK by 2040.

The current deployment of alternative fuels in the UK was assessed using data from the Digest of UK Energy Statistics and the Renewable Transport Fuel Obligation. In 2023, renewable fuels made up 7.5% of total road and non-road mobile machinery fuel in the UK. Notably, none of the alternative fuel production pathways selected for this study are currently deployed commercially in the UK.

Estimated future trajectories for the alternative fuels considered in the scope of this study were then assessed. Overall, the deployment of alternative fuels in the UK is expected to

increase significantly to 2040. However, the scale of domestic production of these fuels is less certain. At present, the 14 plants that have received funding under the Advanced Fuels Fund (AFF), as well as four announced green ammonia plants, represent the best estimate of planned domestic alternative fuel production.

Detailed overviews of the key process steps in the production pathways selected for this study were developed. These overviews summarise the most common processes and operating conditions likely to be deployed. Detailed information available in the public domain was found to be limited. This was attributed to the nascency of the industry and the relatively low technology readiness level of the end-to-end processes (typically TRL 5–8).

A workshop was held in an attempt to address these evidence gaps and was attended by ~70 industry stakeholders. Overall, the attendees agreed with the assessment that process data is generally lacking in the literature and noted that where such data is collected by organisations developing the technology, it is considered proprietary.

Using this analysis, the main potential pollutants and their potential sources within each production process were identified and the risk of emissions to land, air and water assessed.

The risks to human health from emissions from fuel production were assessed qualitatively. While enough information was available to identify potential pollutants, this study has highlighted the need for more detailed information on potential emission levels to enable a more quantitative assessment of risks to human health.

Incident management and major accident hazards in the context of alternative fuels were reviewed. Ammonia and methane are already present on many sites, and existing guidance developed for them remains relevant for e- and biomethane.

For alternative forms of diesel and kerosene (e.g., sustainable aviation fuel), the similarity of many of their physicochemical properties to those of fossil analogues means that many existing incident management techniques are likely to still be relevant. However, very limited information was available on some physical and chemical properties of the alternative fuels, which might influence on how they behave in the environment e.g., octanol-water partition coefficients, soil-water partition coefficients, abiotic and biotic half-lives in soil and water etc.

The risks to the management of controlled waters were also discussed, emphasising the importance of effective wastewater management and flue gas cleaning systems to mitigate potential pollutants. The need for stringent regulatory compliance to protect water quality and prevent contamination was highlighted.

List of abbreviations

AC	Activated carbon
AFF	Advanced Fuels Fund
AD	Anaerobic digestion
ASU	Air separation unit
AtJ	Alcohol to Jet
BAT	Best available techniques
BTX	Benzene, toluene, xylene
COMAH	Control of Major Accident Hazard Regulations (2015)
DAC	Direct air capture
DEFRA	Department for Environment, Food & Rural Affairs
DESNZ	Department for Energy Security and Net Zero
DfT	Department for Transport
DNEL	Derived No Effect Level
DUKES	Digest of UK Energy Statistics
EA	Environmental Agency
EAL	Environmental Assessment Level
ECHA	European Chemicals Agency
EQS	Environmental Quality Standards
FAME	Fatty acid methyl ester
FT	Fischer-Tropsch
FT-SKA	Synthesised kerosene with aromatics derived by alkylation of light aromatics from non-petroleum sources
FT-SPK	Fischer-Tropsch synthesised paraffinic kerosene
GHG	Greenhouse gas

HASAWA	The Health and Safety at Work Act (1974)
HBGV	Health-based guidance values
HDO	Hydrodeoxygenation
HDS	Hydrodesulphurisation
HEFA	Hydroprocessed esters and fatty acids
HSE	Health and Safety Executive
HTL	Hydrothermal liquefaction
HVO	Hydrotreated vegetable oil
IEA	International Energy Agency
KOH	Potassium hydroxide
MAPP	Major accident prevention policy
ME	Methyl ester
MSW	Municipal solid waste
NESO	National Energy System Operator
NIEA	Northern Ireland Environment Agency
NRW	Natural Resources Wales
Ofgem	Office of Gas and Electricity Markets
PAH	Polycyclic aromatic hydrocarbons
PM	Particulate matter
PtL	Power-to-liquid
REACH	Regulation on the registration, evaluation, authorisation and restriction of chemicals
RCF	Recycled carbon fuel
RDF	Refuse derived fuel
RFNBO	Renewable fuel of non-biological origin

RHI	Renewable heat incentive
RMM	Risk management measure
RTFO	Renewable transport fuel obligation
RWGS	Reversed water gas shift
SAF	Sustainable aviation fuel
SEPA	Scottish Environment Protection Agency
SKA	Synthetic Paraffinic Kerosene with Aromatics
SPK	Synthetic Paraffinic Kerosene
STFC	Science and Technology Facilities Council
TRL	Technology readiness level
UK	United Kingdom
UKHSA	UK Health Security Agency
VOC	Volatile organic compounds
WGS	Water gas shift

List of units

% m/m	Mass/mass percent
%v/v	Volume/volume percent
µg	Microgram
°C	Degrees Celsius
atm	Atmosphere
g	Gram
h	Hour
kg	Kilogram
Kow	Octanol-water partition coefficient
L	Litre
log	logarithm
m^3	Cubic metre
mg	Milligram
MJ	Megajoule
mL	Millilitre
mm	Millimetre
mol	Mole
Mt	Million tonnes
MW	Megawatt
ng	Nanogram
Pa	Pascal
Percent	Percentage
ppm	Parts per million
ppmv	Parts per million by volume

s	Second
TWh	Terawatt hour
vol%	Percent by volume
wt%	Percent by weight

1 Introduction

The United Kingdom (UK) has a legally binding target to reduce its greenhouse gas (GHG) emissions to net zero by 2050 (UK Government, 2019). “Alternative” fuels will play a crucial role in achieving this target in the transport and industrial sectors (DESNZ, 2021a).

Alternative fuels refer to fuels which are not derived from fossil sources but can be used as a substitute for fossil fuels. They can provide GHG savings compared to their fossil fuel counterparts, with the extent of these savings depending on the specific feedstock used to produce the fuel and the production pathway used.

To date, the deployment of alternative fuels in the UK transport sector has been largely driven by the Renewable Transport Fuel Obligation (RTFO). Launched in 2008, the RTFO places an obligation on fossil fuel suppliers to supply a minimum volume of renewable fuel annually. The scheme covers fuel supplied to the following obligated transport modes (DfT, 2023):

- Road vehicles
- Non-road transports, including non-road mobile machinery
- Maritime, provided the fuel used is a renewable fuel of non-biological origin

In 2023, 3,700 million litres equivalent of renewable fuel was supplied under the scheme, corresponding to 7.5% of total road and non-road mobile machinery fuel for the year (DfT, 2024a).

In addition to the RTFO, the UK Sustainable Aviation Fuel (SAF) mandate came into effect on 1st January 2025. The SAF mandate places a legal obligation on fuel suppliers to supply an increasing proportion of SAF over time (DfT, 2024b). Between the RTFO and the SAF mandate, 19.47% of all fuel supplied by fossil fuel companies for transport in the UK is required to be renewable by 2030 (DfT, 2024c).

The RTFO and the SAF Mandate provide a well-defined trajectory for the anticipated deployment of alternative fuels for use in the obligated transport modes. This trajectory indicates that demand is expected to increase significantly by 2050. This is discussed in detail in Section 3.2.

In addition to the transport sector, the non-domestic Renewable Heat Incentive (RHI) has driven the growth of biomethane production in the UK. According to the Office of Gas and Electricity Markets (Ofgem), the RHI has paid a feed-in tariff for biomethane injected into the grid by eligible installations since 2011 (Ofgem, 2023).

There is also likely to be an increased demand for alternative fuels across the economy, from sectors that are not directly impacted by the RTFO and SAF Mandate. For example, the Climate Change Committee’s advice on the 6th Carbon Budget suggested that 87% of the required 2050 GHG savings from the maritime sector would be delivered by alternative fuels (Climate Change Committee, 2020). Similarly, the 2021 Industrial Decarbonisation Strategy suggested that 20 TWh of fossil fuels will be replaced with low carbon

alternatives by 2030, although this is not limited to alternative fuels in the context of this report, as it also includes renewable electricity and bioenergy (DESNZ, 2021b).

Domestic production of alternative fuels is likely to increase significantly to help meet this demand. For example, the Department for Transport's (DfT) AFF has competitively allocated £135 million in grant funding to support private investment towards the construction of SAF plants in the UK (DfT, 2024d). Where domestic demand cannot be met by domestic production, alternative fuels will need to be imported, stored and transported around the UK.

Considering all these factors, the alternative fuel landscape in the UK is expected to evolve rapidly in the coming years. Within this context, the Environment Agency has an important role in the regulation of new SAF fuel production and storage facilities, as well as in response to incidents, such as fires, spills and leaks. This study has reviewed the main alternative fuels and production pathways likely to be used in the UK by 2050, evaluated their potential environmental impacts, summarised the fuels' physicochemical properties and examined the applicability of existing incident management techniques to these fuels.

2 Alternative Fuels

2.1 Categorisation of alternative fuels

Alternative fuels are most often categorised based on the feedstocks used in their production. This categorisation is generally useful when discussing the sustainability of alternative fuels, where the choice of feedstock has a significant impact on both the GHG savings associated with the fuel and its broader impact on the environment.

The most common categories applied to alternative fuels are biofuels, renewable fuels of non-biological origin (RFNBOs), e-fuels, power-to-liquid (PtL) fuels and recycled carbon fuels. Table 1 defines these fuel categories and provides examples.

Table 1. Categorisations typically applied to alternative fuels based on feedstocks

Alternative Fuel	Definition	Examples
Biofuel	A liquid or gaseous fuel produced using biomass as a feedstock.	Bioethanol, biodiesel, hydroprocessed esters and fatty acids (HEFA)
Renewable fuel of non-biological origin (RFNBO)	A fuel that does not derive any of its energy content from biogenic sources.	Green hydrogen, ammonia
e-fuel	A subset of RFNBOs made from hydrogen produced using renewable electricity and CO_2.	e-methane, e-methanol, e-diesel, e-kerosene
Power-to-liquid fuel (PtL)	A subset of e-fuels, specifically referring to e-fuels that are liquids.	e-methanol, e-diesel, e-kerosene
Power-to-gas fuel	A subset of e-fuels, specifically referring to e-fuels that are gases.	e-methane
Recycled carbon fuel (RCF)	A fuel made from fossil waste that cannot be avoided, reused or recycled.	Synthetic fuels from industrial off-gases

Biofuels are sometimes further categorised as “first generation” (“1G”), “second generation” (“2G” or “advanced”) or “third generation” (“3G”), depending on the feedstock. 1G biofuels are primarily produced from sugar/starchy crops or oil seeds. 2G biofuels exploit other feedstocks, such as municipal or industrial wastes and agri-food residues. 3G

biofuels refer to those derived from algae feedstocks. Additionally, a fuel may also be considered part biofuel and part RCF if the feedstock is a mix of biogenic and non-biogenic materials, e.g., municipal solid waste (MSW).

Feedstocks can be converted to alternative fuels via a number of production pathways which, in addition to feedstocks, may be used to define the fuels. It is the production pathway that influences the chemical and physicochemical properties of the produced fuel. Therefore, in this report, alternative fuels are defined by both production pathway and feedstock.

“Sustainable aviation fuel” or “SAF” is an additional and distinct sub-category of alternative fuels. This categorisation is used for alternative fuels that are suitable for use in aircraft. It is distinct in that the term SAF does not explicitly specify the production pathway (or feedstock) used to produce the fuel. All SAF must be produced according to the ASTM D7566 standard (ASTM, 2024).

2.2 Production pathway selection

The scope of this study allowed for the detailed analysis of 10 alternative fuel production pathways. The following fuels were out of scope:

- Bioethanol and fatty acid methyl ester (FAME, i.e., biodiesel) were out of scope because their production and deployment are already well-established in the UK
- Hydrotreated vegetable oil (HVO) and hydroprocessed esters and fatty acids (HEFA) were out of scope because they have been the subject of previous studies by the Environment Agency
- Hydrogen was out of scope because it is the subject of a parallel ongoing study within the UK Government

Table 2 lists the production pathways selected for detailed analysis in this study. These pathways were selected in agreement with the Environment Agency at the inception of this study. The selected pathways represent those that are more mature; i.e. they have a higher technology readiness level (TRL) and are more likely be deployed to meet the increased demand for alternative fuels in the UK by 2040.

Table 2. Alternative fuels and production pathways selected for analysis in this study

#	Alternative Fuel	Production Pathway
1	Biomethane	Gasification and methanation
2	e-Methane	Methanation (with green hydrogen)

#	Alternative Fuel	Production Pathway
3	Fischer-Tropsch hydroprocessed synthesised paraffinic kerosene (FT-SPK)	Gasification and Fischer-Tropsch
4	Synthesised kerosene with aromatics derived by alkylation of light aromatics from non-petroleum sources (FT-SKA)	Gasification and Fischer-Tropsch
5	Alcohol to jet synthetic paraffinic kerosene (AtJ-SPK)	Alcohol to Jet
6	Synthetic Paraffinic Kerosene with Aromatics (AtJ-SKA)	Alcohol to Jet
7	Sustainable Aviation Fuel / Drop-in diesel	Pyrolysis
8	Sustainable Aviation Fuel / Drop-in diesel	Hydrothermal liquefaction
9	e-Diesel	Fischer-Tropsch (with green hydrogen)
10	Green Ammonia	Haber-Bosch (with green hydrogen)

3 Deployment trajectories

3.1 Current deployment

The current deployment of alternative fuels in the UK was assessed using data from the Digest of UK Energy Statistics (DUKES) and monitoring data from the RTFO, which mandates transport fuel suppliers to ensure a set percentage of fuel marketed is renewable. In 2023, renewable fuels made up 7.5% of total road and non-road mobile machinery fuel in the UK (DfT, 2024a).

Analysis of the RTFO data[1] shows that, in 2023, 1.12 million tonnes (Mt) of bioethanol and 1.29 Mt of biodiesel methyl ester (ME) were supplied under the scheme. This corresponds to about 80% of the total renewable transport fuel supplied to the UK market. The remaining market share includes smaller quantities of other alternative fuels, notably 0.40 Mt of HVO and 0.08 Mt of SAF. All of these fuels are likely to have been supplied to the market blended with fossil fuels. The RTFO data also shows that 0.25 Mt of biomethane were used in transport in the UK in 2023.

Table 3 provides a summary of alternative fuels supplied to the UK in 2023/24. The fuel quantities correspond to the amount of neat fuel delivered to the UK market. It is likely that bioethanol and biodiesel ME are mainly used blended with petrol (i.e., E10) and diesel (i.e., B7), respectively. In the case of drop-in fuels, it is not possible to determine from available data whether these fuels are used as blends or not.

Biogas can also be upgraded to biomethane by removing the CO_2 in the biogas,[2] then can be injected into the natural gas grid. According to DUKES, 1.35 Mt of biogas (upgraded to biomethane) was injected into the grid in 2023. It should be noted that Ricardo's interpretation of these statistics is that this 1.35 Mt of biogas includes the 0.25 Mt of biomethane supplied for transport purposes. This is because biomethane that is used in transport is transported from the producer to the end user through the grid. This is reflected in the RTFO data. Therefore, it is assumed that the biomethane used in transport is accounted for within the DUKES estimate of biomethane injected into the grid.

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[1] The RTFO data is reported in units of volume (i.e., million litre equivalents), as this is the metric on which the scheme operates. In this report, the units of volume have been converted to units of mass (i.e., million tonnes) using UK Government standard conversion values published by Department for Energy Security and Net Zero (DESNZ) to facilitate a more consistent comparison, as mass is independent of pressure and temperature whereas volume is not. In the case of biomethane, RTFO data reports every kg of biomethane as 1.9 equivalent litres.

[2] See López, et al. (2024) for details on biogas upgrading.

Table 3. Alternative fuels supplied to the UK in 2023/24

Alternative Fuel	Volume Supplied[a] (million litres eq.)	Mass Supplied[b] (million tonnes)
Biodiesel ME (inc. off-road biodiesel)	1,453	1.29
Bioethanol	1,408	1.12
Hydrotreated vegetable oil (HVO)	506	0.40
Biomethane (compressed and liquified)	131	0.26
Sustainable Aviation Fuel (SAF), inc. HEFA	97	0.08
Development diesel (inc. FT-Diesel)	42	0.04
Biomethanol	40	0.03
Biogas injected into the grid	n/a	1.35*
Other	33	n/a

a) Volume supplied, in million litres eq., is as reported by the RTFO statistics.

b) Mass supplied, in million tonnes, was calculated by Ricardo from the RTFO data or DUKES (indicated by *) using standard UK Government conversion factors between volume and mass (DESNZ, 2024a).

In terms of the production and supply of these alternative fuels, those currently produced in the UK are biodiesel ME, bioethanol, HVO/HEFA and biomethane. Biomethane is produced by upgrading biogas[2] through a process that removes CO_2 and other contaminants from the biogas, resulting in near-pure methane. In the UK, biogas is produced at landfills (landfill gas), anaerobic digestion (AD) plants and sewage treatment plants (sewage gas). Table 4 shows estimates of domestic biomethane production by process.

The alternative fuels identified in Table 3 and Table 4 are supplied to the UK market either from domestic production or through imports. Alternative fuels produced in the UK (as listed in Table 4) are also exported to the international market. Thus, the quantities reported in Table 3 and Table 4 are indicative of the physical quantities of these fuels that can be expected in the UK. The exception to this is biomethane, where the reported supply is calculated using a mass balance approach. This means that the reported quantities of biomethane do not necessarily physically enter the UK, as they may be injected into the grid elsewhere.

Production of HVO and HEFA in the UK is limited to the Phillips 66 Humberside refinery (ZEMO, 2022). It is not possible to disaggregate HVO/HEFA production based on publicly available information. HVO and HEFA are both products of the hydrogenation of vegetable oil, with the quantities of each fuel produced depending on the specific process configuration. HEFA can range from 20 to 50% of the total product slate (which refers to the output of different products from the refining process), with the remainder comprising HVO and "light ends" (e.g., propane) (Pavlenko et al., 2019).

Notably, no fuels or production pathways assessed within the scope of this study (see Table 2) are currently deployed in the UK at a commercial scale.

Table 4. Estimates of the current levels of domestic production of alternative fuels

Alternative Fuel	Domestic Production (Mt/year)	Reference
Biodiesel ME	0.59	DfT (2022)
Bioethanol[3]	0.40	DfT (2022)
HVO/HEFA SAF	0.17	ZEMO (2022)
Biomethane (injected into the grid)	0.49	DESNZ (2024b)

3.2 Deployment trajectories

The deployment of alternative fuels is anticipated to increase significantly in the UK over the coming years as efforts to decarbonise gather pace. The demand for these fuels is expected to arise from sectors across the economy, including transport, heat and power generation, industry and manufacturing.

However, detailed projections and deployment trajectories for alternative fuels are currently more readily available for the transport, heat, and power sectors, and these form the basis of the discussion below.

Information specific to the deployment of the alternative fuels industry and manufacturing sectors remains limited. Existing studies on industrial fuel switching, such as those by Element Energy (2020) and National Energy System Operator (NESO, 2024), primarily

[3] Note that the UK bioethanol industry is currently operating below its maximum production capacity of 0.71 Mt/year.

focus on the deployment of low carbon hydrogen. As hydrogen is out of scope, these sectors are not covered in the discussion below.

The following sections provide estimates of the deployment trajectories of the fuels considered in the scope of this study.

3.2.1 Biomethane and e-Methane

As noted previously, biomethane in the UK is currently produced by upgrading biogas. This is achieved using membrane technologies, water washing or amine absorption (Environment Agency, 2022a). The upgraded biogas is then typically injected into the gas grid. A recent call for evidence from the Department for Energy Security and Net Zero (DESNZ) indicated that by 2030, the RTFO, Green Gas Support Scheme and Renewable Heat Incentive are expected to support around 0.5 Mt (8 TWh) of domestically produced biomethane, which will be injected into the grid, compared to 0.4 Mt (6.8 TWh) in 2022 (DESNZ, 2024b).

The 2023 Biomass Strategy suggested that, by 2050, the UK will need 1.95 to 2.60 Mt (30 to 40 TWh) of biomethane to cost-effectively meet its net zero targets (DESNZ, 2023). This suggests that by 2040, biomethane demand is likely to be between 1.23 and 1.56 Mt (19 to 24 TWh), assuming a linear increase between 2030 and 2050.

It is anticipated that biomethane will mainly be produced by AD until 2040. In all 2050 scenarios in the Biomass Strategy, most biomethane is expected to be produced by AD (DESNZ, 2023). In the “High Resource” and “High Innovation” scenarios, gasification and methanation with carbon capture and storage are employed to produce biomethane from MSW. However, the strategy also indicates that gasification and methanation are unlikely to be cost competitive until 2050 (DESNZ, 2023). Consequently, it is unlikely that significant quantities of biomethane will be produced from gasification in the UK between 2025 and 2040.

3.2.2 Sustainable aviation fuel

As noted previously, before an alternative fuel can be used in aircraft it must be certified by ASTM International and recognised in the ASTM D7566 standard (ASTM, 2024). This standard defines the minimum physicochemical and combustion properties that the fuels must have.

As of 2023, 11 SAF production pathways had been certified and a further 11 processes were under evaluation (International Civil Aviation Organization, 2023). The approved pathways utilise a variety of processes to convert feedstocks to SAF. This SAF must then be blended with conventional aviation fuel, up to a maximum percentage by volume defined in ASTM D7566, before it can be used. The blended fuel is then considered compliant with ASTM D1655 - Standard Specification for Aviation Turbine Fuels (ASTM, 2022).

The UK SAF Mandate stipulates that, from 2025, 2% of all jet fuel in flights taking off from the UK must be SAF, rising to 10% in 2030 and 22% in 2040 (DfT, 2024e). As part of their response to the second consultation on the SAF mandate, DfT published a set of possible trajectories for SAF deployment in the UK, as shown in Table 5. These trajectories show the anticipated SAF mix in the UK for HEFA, non-HEFA and Power-to-liquid (PtL or "e-fuel") SAF types[4] from 2025 to 2040 (DfT, 2024e).

Table 5 indicates a significant increase in demand for all SAF types by 2040. This demand increase is primarily driven by the increasing obligation (i.e., the required share of total fuel to be supplied as SAF) under the SAF mandate, as the overall demand for aviation fuel is not anticipated to increase significantly in the period to 2040 (DESNZ, 2022).

According to DfT (DfT, 2024e), the annual demand for HEFA produced domestically is not expected to increase significantly by 2030 but will increase by 119% to 0.35 Mt by 2040. Similarly, HEFA imports are expected to increase by 871% to 0.68 Mt by 2030 then remain approximately constant to 2040. The annual demand for non-HEFA SAF is also expected to rise significantly to 0.31 Mt in 2030 and 1.41 Mt in 2040. Similarly, the annual demand for PtL SAF is expected to increase to 0.06 Mt in 2030 and 0.47 Mt in 2040. Overall, HEFA is expected to be the dominant SAF to 2030, but non-HEFA SAF is expected to have the greatest market share from 2038.

Table 5. Anticipated quantities of SAF to be blended into jet kerosene under the UK SAF mandate (DfT, 2024e)

SAF Type	2025 (Mt)	2030 (Mt)	2040 (Mt)
HEFA Domestic	0.16	0.18	0.35
HEFA Imported	0.07	0.68	0.68
Non-HEFA	0.00	0.31	1.41
Power-to-Liquid	0.00	0.06	0.47
Total mandated SAF	0.23	1.24	2.92

The exact production pathways that will be deployed to meet the forecast demand for non-HEFA and PtL SAF are uncertain. Although still mostly at the design stage, the plants

[4] HEFA is produced by hydrotreating waste oils and fats, non-HEFA SAF is produced from non-oil-based feedstocks (e.g., MSW, agricultural residues etc.) using a variety of processes, and PtL SAF uses low carbon hydrogen and CO_2 as the primary feedstocks.

under development as part of the AFF, as presented in Table 6, are likely to be the strongest indicator for domestic production (DfT, 2024d).

Overall, gasification with Fischer-Tropsch (FT) synthesis is the most common pathway for non-HEFA SAF production in the plants listed in Table 6 by 2030. In total, 3 out of 7 of the non-HEFA plants propose to use this technology, accounting for up to 48% of the total annual SAF production from the non-HEFA SAF facilities. These announced FT-based plants primarily intend to utilise municipal solid waste as a feedstock (DfT, 2024d). Several PtL plants have also been announced under the AFF (DfT, 2024d). However, the planned capacity of these facilities is smaller than those intending to produce non-HEFA SAF, reflecting the current lower commercial maturity and feedstock availability (green hydrogen and CO_2) of the PtL pathway.

Table 6. Planned SAF production capacity for UK plants funded by the AFF (DfT, 2024d)

SAF Type	Plant	Planned total capacity (kt/year)	Planned operation
Non-HEFA	Nova Pangaea Technologies	2.7	2025
Non-HEFA	Abundia Biomass-to-Liquids	2.6	2026
Non-HEFA	Lanzatech UK Ltd	79	2026
Non-HEFA	Fulcrum BioEnergy Ltd	83.7	2027
Non-HEFA	Alfanar Energy	124.2	2028
Non-HEFA	Velocys plc (Altalto)	37.4	2028
Non-HEFA	Esso Petroleum Company	179	2030
PtL	OXCCU Tech	7.4	2026
PtL	Willis Sustainable Fuels	14	2026
PtL	Zero Petroleum	6.1	2026
PtL	Arcadia e-Fuels	67.7	2028
PtL	Carbon Neutral Fuels (ASAP-DAC)	12	2027

SAF Type	Plant	Planned total capacity (kt/year)	Planned operation
PtL	Velocys plc (e-Alto)	Unknown	Unknown

3.2.3 Renewable diesel

Renewable diesel refers to FAME, HVO, FT-diesel and e-diesel. While demand for these alternative fuels is likely to arise primarily from the road transport sector, some demand from non-road mobile machinery applications, such as backup diesel generation, is also probable.

As discussed previously, FAME is currently the most widely deployed alternative fuel in the UK. No fully quantitative assessment of the future demand for FAME in the UK is currently available. However, a 2022 consultation on amending the RTFO, published by DfT, suggests that the demand for FAME under the scheme is highly dependent on the uptake of electric vehicles (DfT, 2021). Based on the demand for transport fuels specified in the UK's Energy and Emissions projections (DESNZ, 2022), DfT suggest that the demand for FAME is likely to remain constant to 2030, before declining slightly by 2035. However, under the high EV uptake scenario, the demand for FAME declines slightly by 2030, before reducing by around 50% by 2035 (DfT, 2021). The current RTFO runs until 2035, so no forecasts beyond this point are available. Nevertheless, the anticipated general trend is that the demand for FAME in the UK will continue to decrease as electrification of the transport fleet increases.

The supply of HVO, FT-diesel and e-diesel in the UK is likely to be primarily driven by the production of SAF. HVO is produced as a co-product of HEFA production, while FT-diesel and e-diesel are produced as co-products of FT and PtL SAF production, respectively. Estimates of the available quantities of these fuels in the UK are shown in Table 7, as calculated by Ricardo based on the demand for SAF. In all cases, it is assumed that the SAF produced represented 50% of the total product slate and that diesel corresponded to 25% of the product slate. These assumptions are based on Pavlenko, et al. (2019). For FT-diesel and e-diesel, it is assumed that the demand for non-HEFA and PtL SAF shown in Table 7 will be met entirely by domestic production because no estimates of the amount of non-HEFA SAF likely to be imported are available and estimates of the expected level of PtL SAF imports are highly uncertain, ranging between 15% and 57% (DfT, 2024e). Therefore, the estimates in Table 7 reflect an estimate of the upper bound of these fuels that could be produced in the UK per annum.

Table 7. Estimated quantities of renewable diesel that could be available in the UK from domestic production, calculated by Ricardo

Fuel Type	2025 (Mt)	2030 (Mt)	2040 (Mt)
HVO (from HEFA process)	0.08	0.09	0.18
FT-Diesel (from non-HEFA SAF)	0.00	0.16	0.71
e-Diesel (from PtL SAF)	0.00	0.03	0.24

This analysis shows that the quantity of these alternative fuels available in the UK is likely to increase substantially by 2040. In the near term, HVO is the most significant of these fuels, with 0.08 Mt potentially produced in 2025. However, by 2030, if the planned AFF plants enter production, the supply of FT-diesel (as a coproduct of FT SAF production) will become more significant, with 0.16 Mt produced. FT-diesel will still be the most significant in 2040, with 0.71 Mt produced.

3.2.4 Ammonia

Ammonia is produced using the Haber-Bosch process, which is currently utilised to produce about 176 Mt of ammonia globally each year (Royal Society, 2020). This process typically uses fossil-fuel derived hydrogen (also known as grey hydrogen), produced by steam methane reforming of natural gas.

Ammonia does not contain any carbon atoms and therefore does not generate any CO_2 when combusted. However, ammonia production can have significant associated CO_2 emissions, due predominantly to the use of grey hydrogen (Royal Society, 2020). For example, when using natural gas to produce grey hydrogen, 1.6 tonnes of CO_2 are generated per tonne of ammonia (Royal Society, 2020). Therefore, to maximise the environmental benefits of using ammonia as a fuel, the grey hydrogen used in the production process must be replaced with low carbon hydrogen.

Low carbon hydrogen most typically refers to green or blue hydrogen.[5] Green hydrogen is produced via the electrolysis of water using renewable electricity. Blue hydrogen is produced via the same route as grey hydrogen but utilises carbon capture and storage technology to capture the CO_2 emitted during production.

Demand for ammonia as a fuel will likely be driven by the maritime sector. The 2021 UK Hydrogen Strategy suggested that the demand for hydrogen-based fuels from domestic and international shipping, principally in the form of ammonia, could increase significantly

[5] Low carbon hydrogen may also refer to “pink” hydrogen, produced via electrolysis of water using nuclear electricity.

between 2030 and 2035 (DESNZ, 2021c). However, the UK Hydrogen Strategy also noted that it was likely to be the mid-2030s before the UK's hydrogen infrastructure would be able to support "green" ammonia production. It suggested that demand could reach 75 to 95 TWh by 2050, which was equivalent to 14.5 to 18.4 Mt of ammonia[6] (DESNZ, 2021c).

The 6th Carbon Budget also provided a trajectory of the demand for domestically produced ammonia for the maritime sector in the UK under a series of potential future pathways (Climate Change Committee, 2020).

Table 8. Forecast demand for domestically produced ammonia for the UK maritime sector (Climate Change Committee, 2020)

Pathway	2030 Ammonia from domestic production (Mt)	2035 Ammonia from domestic production (Mt)	2040 Ammonia from domestic production (Mt)
Balanced	0	4.3	6.8
Widespread Engagement	0	0.2	2.3
Widespread Innovation	0	7.4	11.6

The results for the pathways[7] are presented in Table 8. The magnitude of these estimates is broadly consistent with those from the 2021 UK Hydrogen Strategy. The trajectories show that demand for ammonia as a shipping fuel is not expected to materialise until the mid-2030s. Furthermore, there is significant uncertainty in the projected uptake of ammonia as a shipping fuel. The estimated demand also varies significantly between the scenarios, from 0.2 to 7.4 Mt in 2035, and 2.3 to 11.6 Mt in 2024. The overall demand for ammonia could even be higher than that shown in Table 8, as ammonia could also be imported. The 6th Carbon Budget report suggested that an additional 3.5 Mt of ammonia could be imported in 2050 under the balanced pathway. This is equivalent to 21% of the

[6] Note that is not expected that all of this ammonia would be supplied from UK domestic production.

[7] The 6th Carbon Budget pathways reflect different potential futures and are intended to explore a range of ways to reach net-zero by 2050. The balanced pathway aims to keep as many routes to net zero in play as possible. The widespread engagement pathway assumes higher levels of societal and behavioural change. The widespread innovation pathway assumes greater success in reducing the costs of low-carbon technologies. For more details see Climate Change Committee (2020).

total estimated demand for 2050. No figures were provided for imports between 2030 and 2040.

There is currently no large-scale ammonia production from zero/low carbon hydrogen production in the UK; however, there are several active demonstrator projects. The Ammonia Synthesis Plant from Intermittent Renewable Energy is a green ammonia demonstrator project that became operational in December 2025 (STFC, 2025; Innovation News Network, 2026). The International Energy Agency's (IEA) Hydrogen Production and Infrastructure Projects Database (IEA, 2024a) suggests that there are three projects planned in the UK that intend to either produce ammonia or utilise it as a fuel. H2 Green's green energy hub at Shoreham port intends to develop an ammonia importation facility (Getech, 2021), Hammars Hill and Ensus Energy intend to produce ammonia in Orkney (Hammars Hill Energy, 2020), and ScottishPower are considering ammonia production at their planned Felixstowe green hydrogen fuels hub (ScottishPower, 2022). All of these projects are at the feasibility study stage, so no operational dates are available. The announced capacity of these plants is between 2.2 and 17.3 kilotonnes of hydrogen per year, equivalent to approximately 0.01 to 0.1 Mt of ammonia.

4 Production Pathways

This section gives an overview of the key process steps in the production pathways selected for this study. It also identifies the main potential pollutants and their sources for each production process, and assesses the risk of emissions to land, air and water.

In general, the production pathways covered in this study have not yet been deployed at significant commercial scale and range from TRL 5 to 8. As noted in Section 3.1, none of the fuels within the scope of this study are currently produced in the UK, although several plants are at the design stage. This is also true globally, where technologies for producing advanced biofuels (CETO, 2024) and e-fuels (European Commission, Joint Research Centre, 2024) have not yet reached market maturity and plants remain largely in the design and demonstration phases.

Due to the relatively low level of technology maturity, detailed public domain information on these processes remains limited. In many cases, multiple plant configurations are possible. Since these technologies are still developing, best practices on the optimal plant design have not yet been established and may vary by technology provider. As such, the following sections focus on a representative configuration for each production pathway. It should be noted, however, that new plants may adopt proprietary configurations or equipment that differ from those described here.

4.1 Existing production infrastructure

This section provides an overview of the existing, operational production infrastructure for the alternative fuel pathways under consideration in this study. A review of key literature sources was conducted to identify operational plants worldwide with a minimum TRL of 6, meaning they are at demonstration scale or beyond. The sources reviewed include:

- European Technology and Innovation Platform's production facilities database (European Technology and Innovation Platform Bioenergy, 2025)
- IEA Bioenergy global database of biomass conversion facilities (IEA Bioenergy, 2024a)
- IEA Bioenergy Task 33: Gasification of Biogenic and Waste Feedstocks for a Sustainable Future (IEA Bioenergy, 2024b)
- IEA Hydrogen Production and Infrastructure Projects (IEA Bioenergy, 2024a)

Table 9 provides a summary of the number of plants in operation by pathway, and the range of plant capacities.

Among the pathways reviewed, the pyrolysis process has the highest number of operational plants. However, most of these plants produce pyrolysis oil, an intermediate product that requires further refining to produce sustainable aviation fuel (SAF) or drop-in diesel. Other pathways with operational plants include gasification and methanation to

produce biomethane, gasification and Fischer-Tropsch process to produce FT-SPK, AtJ-SPK to produce synthetic kerosene, and Fischer-Tropsch to produce e-diesel.

Table 9. Overview of existing operational production infrastructure

Alternative Fuel	Production Pathway	Number of plants in operation	Capacity range [tonnes per year]
Biomethane	Gasification and methanation	5	0.1–1,500
e-Methane	Methanation	1	Unknown
Fischer-Tropsch hydroprocessed synthesised paraffinic kerosene (FT-SPK)	Gasification and Fischer-Tropsch	12	1–360
Synthesised kerosene with aromatics derived by alkylation of light aromatics from non-petroleum sources (FT-SKA)	Gasification and Fischer-Tropsch	0	n/a
Alcohol to jet synthetic paraffinic kerosene (AtJ-SPK)	Alcohol to Jet	2	200–27,000
Synthetic Paraffinic Kerosene with Aromatics (AtJ-SKA)	Alcohol to Jet	0	n/a
Sustainable Aviation Fuel / Drop-in diesel	Pyrolysis	22	0.1–36,000
Sustainable Aviation Fuel / Drop-in diesel	Hydrothermal liquefaction	0	n/a
e-Diesel	Fischer-Tropsch	5	0.002–1
Green Ammonia	Haber-Bosch with green hydrogen	7	338–4,237

No operational plants were identified for the remaining pathways. However, globally there are many plants expected to become operational in the next 5–10 years. These include a pilot facility using hydrothermal liquefaction (HTL) technology from FireFly green fuels due

to be built in 2027 in the UK, with a commercial-scale plant following in 2028–2029 (Firefly, 2024). Elsewhere, Swedish Biofuels plan to develop an AtJ-SKA plant in 2025 (Swedish Biofuels, 2023). In addition, various funding mechanisms are in place to support the development of new plants. The UK Government's AFF has allocated over £135 million for developing sustainable aviation fuel (SAF) production plants in the UK. These include several AtJ plants, as well as gasification and Fischer-Tropsch plants to produce SAF.

4.2 Feedstocks for thermochemical production pathways

A wide range of feedstocks are suitable for the thermochemical production pathways (i.e. gasification and pyrolysis), including a range of lignocellulosic biomass such as agricultural and forestry residues, energy crops, and a range of waste feedstocks, such as MSW, refuse derived fuel (RDF) and industrial waste. The feedstock used influences the composition of the product gas (or syngas) from the first process step (gasification) and determines the contaminants it contains. This, in turn, critically impacts the design and operation of downstream gas cleaning processes.

4.2.1 Impacts of feedstock composition on process design

Table 10 presents typical compositions for some biomass and waste feedstocks. It highlights that energy crops and straw generally contain significantly higher levels of chlorine, sulphur, and ash than do wood or woody-based biomass (e.g. short rotation forestry). As a result, utilising these fuels is likely to necessitate additional gas cleaning measures to address potential challenges such as increased emissions, corrosion risks, or contamination of downstream processes, including catalyst deactivation and oil degradation. While tar formation[8] is influenced mostly by the operating conditions of the gasifier and less by the composition of the feedstock, the opposite is true for non-tar components. For these, the composition of the feedstock plays a crucial role in determining the nature and concentration of impurities present in the product gas downstream of the thermochemical conversion process.

Table 10. Composition of several biomass and waste feedstocks, using average values from many samples per feedstock type, from the Phyllis database (www.phyllis.nl)

Feedstocks	C (wt%)	H (wt%)	O (wt%)	N (wt%)	S (wt%)	Cl (wt%)	Ash* (wt%)	H_2O** (wt%)
Untreated wood	48.8	6.0	44.6	0.4	0.03	0.02	1.6	12.8

[8] For more details, see Section 4.3.3

Feedstocks	C (wt%)	H (wt%)	O (wt%)	N (wt%)	S (wt%)	Cl (wt%)	Ash* (wt%)	H_2O** (wt%)
Treated wood	50.7	6.1	41.7	1.2	0.11	0.08	2.7	17.8
Energy crops	49.2	6.0	43.5	0.9	0.16	0.38	3.6	15.4
Straw	50.5	6.1	41.3	1.1	0.15	0.48	10.9	6.1
Refuse Derived Fuel	51.8	7.2	39.3	1.1	0.4	0.39	15.0	25.0
Municipal Solid Waste	56.0	5.1	26.6	1.2	0.5	1.13	39.6	34.8

* Dry basis
** As received

Key factors affecting impurity formation include (National Energy Technology Laboratory, 2022; Zwart, 2009; IEA Bioenergy, 2018):

- **Ash content**: Feedstock with high ash content, such as wastes or fast-growing types like grass and straw, can contain high levels of alkali salts, particularly potassium. These can volatilise at typical gasification temperatures (~800°C), leading to deposition on cooler surfaces downstream or the formation of small particulate matter (PM).
- **Heavy metals**: Waste feedstocks can contain trace amounts of heavy metals such as arsenic, selenium, and mercury, which can be converted to gaseous species during gasification and pose risks to catalysts and the environment.
- **Chlorine compounds**: Chlorine is present in most biomass feedstocks, though chlorine concentrations can be extremely low, such as 0.02wt% in the case of untreated wood. High chlorine content in the feedstock (e.g. grass, straw or waste feedstocks) can lead to higher concentrations of HCl in the product gas.
- **Sulphur compounds**: Sulphur present in the biomass is mainly released as hydrogen sulphide (H2S) and carbonyl sulphide (COS), and only in small amounts as organic sulphur (mercaptans and thiophenes, especially at lower gasification temperatures). The concentration of the S-components depends on the sulphur content of the feedstock, and the exact ratio of sulphur components (H2S, COS, and organic sulphur) is mainly determined by the gasifier operating temperature. Removal of the sulphur components requires robust acid gas removal (AGR) units to meet stringent specifications for sensitive applications like FT synthesis.
- **Nitrogen compounds**: Nitrogen present in the feedstock leads to the formation of ammonia (NH3) and hydrogen cyanide (HCN) during gasification. References to benzyl cyanide, indoles and quinolines have been identified (IEA Bioenergy, 2018).

In this report, these nitrogenous species are classified as tar compounds in line with the adopted tar definition. Both the structural formula and the content of fuel nitrogen in the feedstock significantly affect the formation and evolution of nitrogen species during gasification. Additionally, the introduction of steam in the gasification process has been found to play an important role in converting a large proportion of the feedstock-N into NH3 and HCN. These species can contribute to operational challenges and require appropriate gas-cleaning measures.

Selecting the appropriate feedstock is a critical factor in designing a gasification-based system, as it not only determines the type and concentration of contaminants in the product gas but is also influenced by the requirements of the downstream processing and the final fuel to be produced. The characteristics of the chosen feedstock affect the complexity and cost of gas cleaning processes, as well as the composition of the pollutant streams generated – such as solid waste (such as ash and spent sorbents), wastewater containing dissolved impurities, and gaseous emissions from treatment operations – all of which require appropriate environmental management. For instance, in thermochemical conversion systems such as gasification and pyrolysis, switching from a low-ash, low-sulphur wood-based feedstock to an agricultural residue with higher-ash and sulphur content would increase the burden on particulate matter (PM) and acid gas removal systems. Additionally, it could introduce new contaminants, such as high levels of potassium and chlorine, necessitating modifications to downstream processing requirements and affecting the composition of byproduct streams.

4.2.2 Feedstock pretreatment

Pretreatment may be required to prepare the feedstock for the thermochemical conversion processes. The exact requirements for pretreatment depend on the type of feedstock (e.g., biomass or waste), and the process requirements, such as the plant feeding system, the chosen conversion technology, the processing capacity, etc. Common pretreatment processes are summarised in Table 11 below (Department for Business, Energy & Industrial Strategy, 2021).

Table 11. Summary of pre-treatment processes used for biomass feedstocks

Pretreatment process	Purpose
Drying	Reduce the moisture content to the maximum allowed by the specific gasification technology (on average 10-30 wt% for gasification and 5-15 wt% for pyrolysis (Jahirul et al., 2012), to increase the overall thermal efficiency of the thermochemical conversion process, due to the reduced need for water evaporation.
Pelletising	Increase the bulk density to facilitate efficient transportation and storage, reduce possible degradation and facilitate feeding into the

Pretreatment process	Purpose
	reactor. Although the lignin in wood is typically sufficient to bind pellets, other types of feedstock often require additional processing to enhance their durability. In some cases, binders like starch, sugars, vegetable oils, or lignin are added to improve the quality of the pellets. As a result of the bulk density increase, the product yield is also increased (i.e., kg of fuel per kg feedstock).
Shredding and chipping	Reduce the size of the feedstock and create a uniform particle size for inhomogeneous materials, e.g., woody biomass. The particle size depends on the conversion technology and feeding system and ranges between 0.1–50mm for gasification and 0.1–20mm for pyrolysis (Jerzak et al., 2024; National Energy Technology Laboratory, 2022).
Screening and metal separation	Using screens and magnets to remove some foreign materials, such as metal, stone or glass, fragments which are too thin or too large from feedstocks like waste wood and RDF or agricultural waste (introduced during harvesting and transportation). These materials must be removed because they can damage the feeding system of the conversion reactor. The acceptable concentrations of these materials depend on the conversion technology and conditions (e.g. temperature). For example, fluidised bed reactors cannot tolerate coarse materials or metals/glass, as they will cause bed-related problems such as defluidisation. On the other hand, plasma reactors operating at high temperatures (typically above 2000°C) can process glass, metals or stones. Also, if the temperature is too high – which is desirable for plasma reactors but not for other designs – it might cause metal oxidation or glass melting, so the reaction temperature needs to be adjusted to the feedstock, or the feedstock to the reactor conditions/technology.

4.3 Biomethane via gasification and methanation

4.3.1 Process description

A process diagram for biomethane (also called Substitute Natural Gas or Synthetic Natural Gas) production via gasification and catalytic methanation is presented in Figure 1. There are many potential variations of the process configuration, depending on the feedstock and gasification technology selected. However, the general process steps are common and include feedstock pre-treatment, feedstock conversion, gas cleaning, gas conditioning, and fuel synthesis and upgrading.

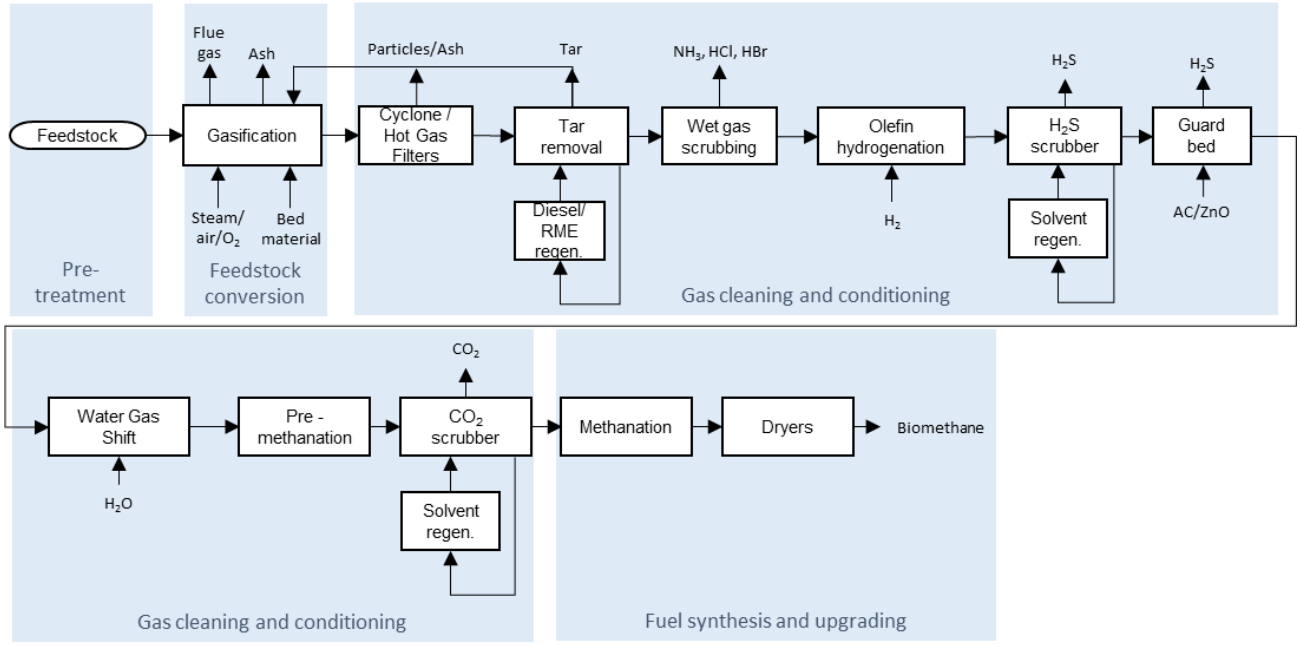

Figure 1. Process diagram for the production of biomethane by gasification and methanation

4.3.2 Feedstock pretreatment

Feedstock pretreatment may be required to prepare the feedstock for the gasification process. The exact requirements for pretreatment depend on both the type of feedstock and the chosen gasification technology. Common pretreatment processes are summarised in Table 11. Sites can either carry out feedstock pretreatment or receive feedstock that is already prepared for use.

4.3.3 Feedstock conversion

Gasification is a thermochemical process with a TRL of 8–9 that converts carbon-containing feedstocks into a product gas at medium to high temperatures (600–1,300°C) (European Biogas Association, 2024a). The process is also known as partial oxidation of a carbon-containing material, with less oxygen than the stoichiometric requirement for complete combustion. The oxygen can be supplied via different gasification media such as

air, oxygen, steam, carbon dioxide, and a combination of these. However, for biomethane production and the synthesis of other fuels, air is avoided to limit nitrogen dilution of the product gas (van der Meijden, 2010). Various different gasification technologies, such as entrained flow, fixed and fluidised beds, have been commercialised or demonstrated to date and are discussed in more detail below.

The term “synthesis gas” or “syngas” is commonly used in the industry as a general reference to the product gas from gasification. However, syngas technically consists of carbon monoxide (CO) and hydrogen (H_2). Other components of the product gas include carbon dioxide (CO_2), methane (CH_4) and low concentrations of other light hydrocarbons, such as C2s (C_2H_6, C_2H_4, C_2H_2), C3s (C_3H_8, C_3H_6) and C4s–C6s (C_4H_{10}), benzene, toluene and xylenes (BTX), tar (including polycyclic aromatic hydrocarbons (PAHs)). Tar is defined as all the condensable organic hydrocarbons of molecular weight higher than benzene (Maniatis & Beenackers, 2000). Other impurities include S- and N- compounds, such as hydrogen sulphide (H_2S), carbonyl sulphite (COS), thiophenes, mercaptans, ammonia (NH_3) and hydrogen cyanide (HCN) (IEA Bioenergy, 2018). In addition, particulate matter (PM), dust, silica, alkali and other metal traces can be entrained with the product gas. Nitrogen (N_2) may also be present if air is used as a gasification agent. Concentrations of all gasification products in the outlet streams will show minor variations depending on the feedstock, gasification conditions and gasification technology (i.e. type of gasifier) used.

Gasification technologies might have different configurations depending on the feedstock-gasification agent interactions and whether a bed material is used. The operating temperature can also be used as a parameter to classify the reactor types; for example, high-temperature and medium-temperature gasifiers can be categorised based on their operating temperatures and how the feedstock interacts with the gasification agent (van der Meijden, 2010):

- High-temperature gasifiers, such as Entrained Flow (EF) gasifiers, operate at temperatures above 1,300°C and pressures around 3000 kPa. They primarily produce syngas, which contains minimal hydrocarbons (with nearly zero tar) (National Energy Technology Laboratory, 2022). EF gasifiers, commonly used for coal, require fuel to be pulverised and are always operated above the ash melting temperature to prevent solid deposits. While biomass can theoretically be used in these types of gasifiers, it requires special treatment i.e. milling, which has a high energy requirement. This, together with challenges around feeding difficulties, make direct application difficult. Pretreatment methods like torrefaction are being explored, to reduce the required milling energy, but the overall efficiency remains uncertain.
- Medium-temperature gasifiers, typically operating at around 850°C, include Fixed Bed (downdraft and updraft) and Fluidised Bed (bubbling, circulating, and indirect) gasifiers. Downdraft gasifiers are well-suited for small-scale applications due to their relatively clean gas output, but struggle with scalability and require dry, well-defined fuel. Updraft gasifiers handle a wider range of feedstocks and scale better but produce high tar levels (1 to 10 wt%) (National Energy Technology Laboratory,

2022), requiring costly tar removal systems. Neither Fixed Bed gasifier is ideal for large-scale biomethane production due to nitrogen contamination when air is used as a gasification agent. Fluidised Bed gasifiers offer better scalability and fuel flexibility. Bubbling Fluidised Bed and Circulating Fluidised Bed gasifiers distribute heat evenly, preventing hot spots and improving gasification efficiency. All Fluidised Bed gasifiers use a bed material. This may be sand or a catalytically active bed material like olivine. They can produce nitrogen-free gas, making them suitable for biomethane production. Indirect or allothermal gasifiers utilise twin-bed designs to separate the combustion and gasification zones, enhancing efficiency. However, all fluidised-bed gasifiers require specialised bed materials, and catalytic options like dolomite or olivine are often used to reduce tar formation.

Indirect Dual Fluidised Bed gasification, typically using steam as the gasification medium at temperatures below 1,000 °C, is the most efficient technology for biomethane production (van der Meijden, 2010). This is because methane constitutes a large proportion of the product gas under these conditions (approximately 10 vol% on dry basis; Larsson et al., 2018), as opposed to a pure syngas (i.e., H_2 and CO), which contains no methane. This gasification system is a two-reactor system, with one gasification reactor and one combustor reactor. During the process, the selected feedstock is fed to the gasification reactor, where it is devolatilised and gasified with steam. The unconverted part of the feedstock (char) is transported with the bed material to the combustion reactor, where it is burnt with air to generate heat for the process (Larsson et al., 2018). The flue gas produced from the gasifier's combustor mainly contains CO_2, N_2 and O_2, as well as traces of NO_x and hydrocarbons. This gasification technology has been commercialised by several companies including ENGIE, REPOTEC and SYNOVA (IEA Bioenergy, 2024b).

4.3.4 Gas cleaning and conditioning

Gas cleaning is necessary to remove the main impurities present in the product gas produced from the gasification reactor. Table 12 summarises the main impurities that need to be removed.

Table 12. Syngas impurities and processes used for their removal

Common syngas impurities	Processes for removal
Particulate Matter (PM)/Dust (unburned carbon and ash)	Cyclones, hot gas filters, electrostatic precipitators and wet scrubbers are all used, often in combination, depending on the specific plant design. Generally, a combination of cyclones followed by either wet scrubber or candle filter can remove 99.9% of particulates (National Energy Technology Laboratory, 2022).

Common syngas impurities	Processes for removal
Alkali and heavy metals, such as Arsenic (As), Cadmium (Cd), Cobalt (Co), Chromium (Cr), Copper (Cu), Mercury (Hg), Lead (Pb), Selenium (Se), Zinc (Zn), Titanium (Ti) and Vanadium (V)	These can be removed by a filtration unit (e.g. by hot gas filters). Traces of metals can be removed by activated carbon (AC) beds. This is typically used as guard bed downstream bulk removal processes, due to operational problems related to waste disposal. Spent carbon waste can be landfilled or incinerated. It can also be regenerated with a gas stream, but this tail gas may then require treatment. Alternatively, the metals can be removed with wet scrubbers. In this case, the metals become entrained in the liquid (typically water), which is collected and generally requires treatment prior to discharge.
Tar (high molecular weight (heavy) hydrocarbons, such as Naphthalene or Phenols) and BTX	Tar concentration depends on the feedstock, gasification conditions and technology. Tar can be converted (i.e. cracked or reformed) to H_2 and CO via thermal, plasma or catalytic cracking or reforming. Alternatively, it can be removed by wet scrubbing (with oil or water), where oil can be regenerated, and the tar stream can be recirculated to the gasifier. Adsorption on solid sorbents (e.g. active carbon) is typically used downstream as a guard bed. The choice of the appropriate technology depends on the specific plant design. Decision factors include the efficiency and technological readiness of each process, catalyst activity, etc.
N-compounds	NH_3 can be removed by acid wet scrubbing, reacting with an aqueous solution of sulphuric acid, to form ammonium sulphate ($(NH_4)_2SO_4$), which is then removed. The concentration of sulphuric acid depends on the NH_3 concentration in the product gas. NH_3 can also be converted by catalytic hot gas cleaning methods using iron-based, nickel-based and alkaline earth metal oxide catalysts to hydrogen and nitrogen (Wang & Pang, 2018). The selection of different methods is influenced by plant design and economic considerations, as one process may achieve higher removal efficiency but result in lower overall process efficiency due to temperature fluctuations. Hydrogen cyanide (HCN) concentration depends on different factors, mainly the feedstock composition (N content) and the gasification conditions (such as residence time and heating rate) (Dagaut et al., 2008). Data on HCN concentration in biomass gasification in the literature are limited, with variations

Common syngas impurities	Processes for removal
	in measurement and capture methods, as no single standard approach is applied widely. The comparison of values is further complicated by variations in the reference basis used for reporting, such as dry or wet basis, or N_2-free normalisation. Reported values include (Larsson et al., 2018; Liakakou et al., 2019; Grootjes et al., 2016): • 0.001% from gasification of woody biomass at 800-850°C • 0.01% (on dry basis) from gasification of softwood lignin feedstock at 870°C • 0.13% (on dry basis) from gasification of wheat straw lignin feedstock at 780°C • 0.25% from gasification of plastic waste feedstock at 750°C • 0.30% from gasification of pelletised industrial waste feedstock at 750°C HCN traces can be removed by adsorption on AC impregnated with metal salts which produces a solid sorbent waste or by physicochemical adsorption. This requires water or tail gas treatment, which produces an acid gas-rich waste stream. The selection of different methods is influenced by plant design and economic considerations, as one process may achieve higher removal efficiency but result in lower overall process efficiency due to temperature fluctuations.
Halogenated compounds (HCl, HBr, HF)	Can be removed by wet scrubbing/absorption (exothermic: high water to gas ratio, acidic wastewater effluent), usually with a base like $Ca(OH)_2$, NaOH (solvent typically not regenerated). Feedstocks which include plastic may contain halides, depending on the specific types of plastics in the feedstocks. PVCs and flame-retardant plastics are the primary contributors to halide presence in the resulting syngas. When gasifying waste feedstocks such as Refuse Derived Fuel (RDF) or Solid Recovered Fuel (SRF), plant operators typically remove these plastics from the feedstock to simplify the gas cleaning operations.
Sulphuric compounds (H_2S,	Hydrolysis can be used to convert carbonyl sulphite (COS) and other organic sulphur compounds to hydrogen sulphide (H_2S). Different methods can be used to remove H_2S:

Common syngas impurities	Processes for removal
COS, organic sulphur compounds)	1. Physical absorption using a liquid solvent (Selexol or Rectisol) that also removes CO_2 and can also remove COS and HCN. Physical solvents can be recovered with relative ease by changing the temperature, to reduce the solubility of the acid gases (like H_2S and CO_2) in the solvent. However, treatment of the acid gas-rich stream is more complex. A sulphur recovery process, such as the Claus process (a commercial system that converts H_2S from the acid gases into elemental sulphur through a series of chemical reactors and condensers), may be needed to treat H_2S-containing gas for safe disposal. Alternatively, H_2S can be desorbed and utilised as a by-product. 2. Dry adsorption using ZnO, AC, and zeolite sorbents. If ZnO is used, sulphur can be found in the spent sorbent in the form of zinc sulphide (ZnS). When AC is used, this is typically impregnated with metal oxides, so metal sulphides may form in the spent sorbent. In case of zeolites, if these are ion-exchanged with metals, metal sulphides may form. Spent sorbent waste must be landfilled or incinerated. Most commercially-available sulphur removal technologies are adaptations of existing processes designed for acid gas removal, primarily targeting H_2S and CO_2 in raw natural gas and other industrial gases. When selecting a sulphur removal technology, project developers prioritise its efficiency in selectively removing sulphur compounds. The second key consideration is whether the technology can also achieve the required level of CO_2 removal. Another important factor is the ability to generate a sulphur by-product stream that either is directly marketable or requires minimal further processing, such as conversion to elemental S in a Claus unit.
Carbon dioxide (CO_2)	Different methods can be used to remove CO_2: 1. Physical absorption using a liquid solvent (Selexol or Rectisol), as mentioned previously. 2. Chemical absorption using amine scrubbing. Absorption takes place in an absorber column, at 40–70°C – amines can be regenerated in a stripper

Common syngas impurities	Processes for removal
	column, by increasing the temperature to about 100–120°C (Rochelle, 2012).

Although the major impurities have already been removed from the gas, some further conditioning is still required to meet the requirements of the downstream catalytic synthesis. Table 13 summarises common gas conditioning processes.

Table 13. Summary of the gas conditioning processes commonly used to produce biomethane

Gas conditioning process	Purpose
Water gas shift (WGS)	Converts CO and H_2O to CO_2 and H_2. Used to increase the H_2 content of syngas; typically uses a Fe-, Cu- or Co-based catalyst, at 200-500°C.
Pre-reforming	Converts C2+ compounds to CH_4 and/or syngas, typically under a Ni-based catalyst.
Catalytic hydrogenation	Saturates any unsaturated hydrocarbons (olefins) that may be present in the syngas.
Pre-methanation	The pre-methanation reactor acts as a reformer for all hydrocarbons heavier than methane (C_{2+} hydrocarbons), typically using a Ni-based catalyst, in the presence of CO_2 for temperature control.
CO_2 removal	Removes CO_2, typically follows the pre-methanation.

In this process configuration, CO_2 and H_2O are removed at the end of the process, as they help minimise the chances of runaway in the exothermic methanation reactors.

Table 14 describes the possible unit operations in the gas cleaning and upgrading processes, downstream gasification.

Table 14. Matrix of gas cleaning and conditioning unit operations that could be applied downstream gasification

Process	Unit operation	Input	Process conditions and additional input (chemicals or catalysts)	Key process output	Additional outputs	Notes
Gas cleaning						
Filtration	Cyclones	Product gas	300–600°C (above tar dew point)	Product gas (excl. PM)	PM (large particles (≥5μm))	Efficiency is around 90% Often cannot meet the particulate removal targets needed to protect downstream equipment alone (often combined with multiple colder cyclones, hot gas filters, electrostatic precipitators or wet scrubbers)
	Hot Gas Filters	Product gas	450–500°C (above tar dew point)	Product gas (excl. PM)	Fine PM (0.5–100μm) Condensed alkali/heavy metals	Typically used downstream cyclones to reduce the overall particulate load Reduced efficiency for <0.1 μm particles
	Electrostatic precipitators	Product gas (typically after bulk	40–50°C	Product gas (excl. PM)	Removal of very small PM	Suitable for removal of aerosols and small droplets

Process	Unit operation	Input	Process conditions and additional input (chemicals or catalysts)	Key process output	Additional outputs	Notes
		PM and tar removal)			particles (<0.1µm)	Not suitable if there is a high explosion risk Typically uses downstream cooling and tar scrubbing removal (Zwart, 2009), in which small particles present in the gas (e.g. ash, aerosols) grow in particle size due to condensation of a liquid on the particle, namely water, RME or oil. As such, an electrostatic precipitator also becomes suitable for small particles, and hence very high separation efficiencies can be obtained.
Tar removal	Wet scrubbing	Product gas (after PM removal)	Below tar dew point (e.g. <350°C) when using organic solvents (e.g. RME) 75°C when using water	Product gas (excl. PM, tar)	Tar PM >0.1 µm	Requires solvent regeneration when organic solvents are used – tar stream is combusted in the gasifier

Process	Unit operation	Input	Process conditions and additional input (chemicals or catalysts)	Key process output	Additional outputs	Notes
						Generates tar-contaminated water that requires treatment when water is used Fine particles (which can contain alkali and heavy metals) still present in the gas can be entrained in the liquid
Tar conversion	Reforming/ cracking (e.g. catalytic, thermal, plasma)	Product gas (after PM removal)	600–1,200°C Zr, Ni, noble metals, zeolites and natural catalysts (e.g. dolomite, magnesite, calcite, olivine)	Product gas (excl. PM, tar)	Spent catalyst	Results in increased syngas (H_2 & CO) yield
Chloride removal	Wet scrubbing	Product gas (after PM, tar removal)	Ambient temperature Water or caustic water solution (e.g. $Ca(OH)_2$. NaOH)	Product gas (excl. PM, tar, HCl)	Wastewater containing Cl if water is used Wastewater containing salts	The amount of water present in the product gas should be able to remove ~500 ppm of HCl/HBr/HF when condensing; wastewater requires additional water treatment (e.g. an ionic exchanger)

Process	Unit operation	Input	Process conditions and additional input (chemicals or catalysts)	Key process output	Additional outputs	Notes
					if caustic water is used Other acid gases (like COS, H_2S and CO_2) can also be removed depending on the residence time (Zwart, 2009).	If caustic water is used (e.g. aqueous NaOH solution), HCl is removed effectively, forming stable salts (e.g. NaCl)
N-compounds removal (NH_3, HCN)	Wet scrubbing	Product gas (after PM, tar removal)	Ambient temperature Aqueous solution of H_2SO_4	Product gas (excl. NH_3)	Waste water containing ammonia salts ($(NH_4)_2SO_4$)	-
S-compounds removal	Rectisol	Product gas (after PM, tar removal)	>3000 kPa -30 to -75°C Methanol solvent	Product gas (excl. H_2S, CO_2)	Can achieve low concentrations of H_2S and COS (<0.1 ppmv) and	Solvent can be regenerated using pressure swing and stripping, as well as temperature swing processes. H_2S can be

Process	Unit operation	Input	Process conditions and additional input (chemicals or catalysts)	Key process output	Additional outputs	Notes
(H_2S, COS, organic S)					CO_2 (<10 ppmv). Also removes HCN, NH_3, hydrocarbons, Hg	recovered as elemental sulphur using the Claus process Has been demonstrated for chemical production from gasification systems Typically used for large plant sizes (>25,000 m^3/h)
	Selexol	Product gas (after PM, tar removal)	2000–13000 kPa 5–40°C Dimethylethers of polyethylene glycol	Product gas (excl. H_2S, CO_2)	Can achieve concentrations of H_2S and COS of 1 ppmv and CO_2 (<10 ppmv). Also removes HCN, NH_3, hydrocarbons, Hg	Solvent can be regenerated using pressure swing and stripping, as well as temperature swing processes. H_2S can be recovered as elemental sulphur using the Claus process Typically used for large plant size (>25,000 m^3/h)
	Dry adsorption	Product gas (after PM, tar removal)	250–500°C	Product gas (excl. H_2S)	Spent ZnO or AC bed	Typically used in small systems or as a guard bed downstream from other S-removal methods

Process	Unit operation	Input	Process conditions and additional input (chemicals or catalysts)	Key process output	Additional outputs	Notes
			Solid sorbents (e.g. AC or ZnO beds)			AC beds also remove PM, metals (e.g. Hg), HCN
COS conversion	Hydrolysis	Product gas (after PM, tar, halogens removal)	150–300°C Alumina or Titanium oxide catalysts Steam	Product gas (excl. COS and HCN)	Spent catalyst	Main reaction is the hydrolysis of COS to H_2S HCN into NH_3 also takes place Used if the selected S-removal processes cannot remove enough of the COS to meet target S- specifications
Gas upgrading						
Conversion of unsaturated HCs	Hydrogenation or hydrodesulphurisation (HDS)	Product gas (containing unsaturated hydrocarbons)	300–500°C Elevated pressure (<4000 kPa) H_2, Steam Pt or Pd catalysts	Product gas (excl. unsaturated hydrocarbons)	Spent catalyst	Converts unsaturated hydrocarbons to saturated HDS catalysts can also convert organic S compounds to H_2S and COS

Process	Unit operation	Input	Process conditions and additional input (chemicals or catalysts)	Key process output	Additional outputs	Notes
			HDS catalysts: Co/Mo- or Ni/Mo-			HDS is used instead of separate hydrolysis reactor if S-compounds are still present
H_2/CO ratio adjustment	Sour shift: simultaneous hydrolysis and water gas shift	Product gas (containing S-compounds)	200–300°C 3000 kPa Steam Co/Mo- or Ni/Mo catalysts	Syngas (with increased H_2 content)	Steam	Used when there is still S- in the product gas and there is no separate hydrolysis reactor
	Water gas shift (WGS)	Product gas (S-free)	200–500°C 3000 kPa Steam Fe-, Cu- or Co-based catalysts	Syngas (with increased H_2 content)	Steam	Used downstream of S- removal Typical WGS catalysts require prior removal of inorganic impurities as they cause catalyst deactivation
CO_2 removal	Pressure swing adsorption	Syngas Sorbents	2000–4000 kPa	Syngas (excl. CO_2)	CO_2-rich gas stream	Typically, multiple parallel reactors are required as pressure swing adsorption is a cyclic

Process	Unit operation	Input	Process conditions and additional input (chemicals or catalysts)	Key process output	Additional outputs	Notes
			Ambient temperature Zeolites or AC adsorbents			process, involving adsorption and regeneration steps
	Amines	Product gas (after PM, tar removal)	Amines (e.g. monoethanolamine, methyldiethanolamine) 40–70°C High pressure is preferred (exact operating pressure depends on the system)	Syngas (excl. H_2S, CO_2)	Amine solvent containing CO_2, H_2S	Amines can be regenerated in a stripper column by increasing the temperature to about 100-120°C Depending on the selected amine solvent, this process can remove both CO_2 and H_2S

4.3.5 Fuel synthesis and upgrading

The final steps are fuel synthesis and final product upgrading, which has a TRL of 6–8 (BIOREF Collaborative Laboratory for Biorefineries, 2023). The remaining CO in the gas is converted to methane, in the presence of H_2. Typically, a Ni-based catalyst is used in the methanation reactor. This is usually undertaken at temperatures of 350–375°C (National Energy Technology Laboratory, 2022) and pressures of 100–3000 kPa (Skorek-Osikowska, 2022). The gas after the methanation reactor contains roughly 50% water. The final step involves drying of the gas to remove the water formed during the methanation reaction.

Similar methanation processes are offered by Wood PLC (VESTA technology), ENGIE (GAYA plant) and was applied in the GoBiGas project. An alternative process is offered by Topsoe (TREMP process) (IEA Bioenergy, 2024c).

4.3.6 Water abstraction requirements

Water is required for numerous process steps involved with the production of biomethane by gasification and methanation. These are summarised in Table 15.

Table 15. Water abstraction requirements for biomethane production from gasification

Process step	Water abstraction requirement
Cooling-Systems	Water is required in cooling systems and heat-exchangers to regulate temperature, act as a condenser, and for product quenching.
Gasification	Demineralised steam is typically required as a gasifying agent for the conversion of biomass. In some cases, the moisture in the feedstock can play that role.
Gas Cleaning	Water is required for wet scrubbing, a process to remove numerous particulates and pollutants from the product gas.
WGS Reaction	Water is used as a reactant in the WGS reaction to convert carbon monoxide to carbon dioxide.

There is little information in the literature on the potential quantities of water required for each of these operations in a full-size plant. However, information is available for the GoBiGas demonstration plant, which has a 20MW biomethane output. In this plant the water requirement during start-up is about 0.01L/MJ or 0.5L/kg of methane (Thunman et al., 2018). During stable operation there is no additional water requirement, as the

wastewater is cleaned at an on-site water treatment facility and used as cooling water or to produce ultrapure make-up (boiler grade) water for the steam system (Göteborg Energi, 2018; Eurowater, 2024).

At the GoBiGas plant, as an improvement potential for wastewater management, a system for on-site incineration of wastewater sludge in the combustion reactor was considered.

4.3.7 Pollutants generated during production of biomethane from gasification

Table 16 summarises the products and by-products that have been identified as possible pollutants generated during biomethane production from gasification. During normal plant operation, the risk of these pollutants being emitted to air or water pathways should be low, as biomethane production is undertaken within a closed system. However, there may be a risk of release if venting or purging is required, or during maintenance. As most reactions take place in the gas phase, these releases can occur through pressure relief valves. The pressures of the sub-processes were discussed in a prior section, and are typically as follows:

- Feedstock combustion & gasification – near-atmospheric
- Gas cleaning – 100 to 1000 kPa
- Bridging processes – atmospheric pressure up to 1600 kPa
- Fuel synthesis – 1600 kPa

More details on standard practices for preventing gas leakages are given in Section 4.3.9.

Table 16. Summary of possible pollutants from biomethane production by gasification and methanation

Pathway	Production Step (Source)	Pollutants
Air	Feedstock storage and pre-treatment	Particulate matter and various other pollutants depending on feedstock and the choice of pre-treatment process. Dust and fine particles can be generated during biomass handling, drying, grinding and size reduction. Volatile light hydrocarbons may be emitted during drying or heating of biomass.[9] Sulphur compounds may be released in the case of feedstock containing sulphur.

[9] If the feedstock contains volatile fractions.

Pathway	Production Step (Source)	Pollutants
	Gasification	CO, CO_2, H_2, CH_4, C_{2+} HCs, HCl, HF, H_2S, COS, NH_3, HCN, NOx Tar (including PAHs) and BTX Particulate matter (PM) Alkali and volatile heavy metals (Na, As, Cd, Co, Cr, Cu, Hg, Pb, Se, Zn, Ti, V)
	Gas cleaning and conditioning	CO, CO_2, H_2, CH_4, C_{2+} HCs, HCl, HF, H_2S, COS, NH_3, HCN, NOx Tar (including PAHs) and BTX Particulate matter (PM) Alkali and volatile heavy metals (Na, As, Cd, Co, Cr, Cu, Hg, Pb, Se, Zn, Ti, V)
	Fuel synthesis and upgrading	CH_4, CO_2, CO, H_2
Water	Feedstock storage and pre-treatment	Liquid run off from biomass storage can contain organic matter. Process water (i.e. from washing or hydrothermal pretreatment) may be contaminated with organic compounds, dissolved solids and microbial pathogens. Pre-treatment methods like pyrolysis or torrefaction can generate tar-like substances that may require proper handling. If there are heavy metals in the feedstock, these may accumulate. Ash and char residues may form from partial combustion or torrefaction processes during pre-treatment.
	Gasification	-
	Gas cleaning and conditioning	Tar including PAHs, and BTX Inorganic salts of NH_3, HCl, HCN

Pathway	Production Step (Source)	Pollutants
		Metals: Na, As, Cd, Co, Cr, Cu, Hg, Pb, Se, Zn, Ti, V Dissolved gases: (CO, CO_2, CH_4), H_2S, COS, mercaptans Excess moisture from the process may be contaminated with catalyst dust from the catalytic reactions
	Fuel synthesis and upgrading	Excess moisture from the process may be contaminated with catalyst dust from the catalytic reactions
Land	Unlikely to be any emissions to land	

4.3.8 Emissions to water

A major pathway for potential emissions to water relates to the generation of wastewater during syngas cleaning. During the gasification of biomass feedstocks to syngas, many waste compounds are produced at low concentrations. This includes low aromatic hydrocarbons (e.g. BTX and tar), which are subsequently reformed/cracked or removed from the product gas by wet scrubbing. Many other pollutants that may be present in the product gas stream can also be removed via wet scrubbing, including metals, ammonia (NH_3), hydrogen cyanide (HCN), sulphur compounds and halogenated compounds such as hydrogen chloride (HCl) (National Energy Technology Laboratory, 2022). Amine compounds utilised during this conditioning step are also likely to be present within the waste stream, and have been shown to rapidly degrade into nitrosamines and nitramines within surface water, ground or soil (Eide-Haugmo et al., 2012). Other solvents that can be used in the conditioning steps and may be present within the wastewater include refrigerated methanol (Rectisol) or dimethyl ethers of polyethylene glycols (Selexol). Any contaminants that may have been present in the gas phase can be transferred to the liquid phase via this process (Department for Business, Energy & Industrial Strategy, 2021).

Wastewater generated during syngas cleaning could also contain dissolved gases (CO, CO_2, CH_4), as well as catalysts. Typically, the clean-up process goes in the following order: particulate and tar, acid gas removal (S and Cl), ammonia stripping and metal absorption, followed by the main catalytic reactions, as the catalysts are sensitive to the gas impurities which can cause catalyst deactivation.

The volume of generated wastewater, and the concentration of pollutants within the wastewater, will depend on the choice of feedstock. Different types of biomasses have varying mass concentrations of carbon, hydrogen, oxygen, nitrogen, sulphur and ash

content. Biomass with higher nitrogen content can result in the conversion of higher amounts of ammonia and hydrogen cyanide (Broer & Brown, 2015). While ammonia is typically the dominant form of nitrogen contaminant, higher reaction temperatures can increase hydrogen cyanide concentrations due to secondary reactions occurring (Woolcock & Brown, 2013). Sulphur contaminants produced during biomass gasification, in the form of H_2S, COS or mercaptans, are generally lower than coal, in the range of 0.1 to 30 mL L^{-1}, but depend on the sulphur content of the feedstock (Woolcock & Brown, 2013). The generation of tar is correlated with reaction severity, with longer reaction times and higher temperatures generally resulting in reduced tar yields. Amounts of particulate matter, in the form of soot, dust and ash, vary depending on both the amount of residual solid carbon and other inorganic components such as alkali metals, silica and other metals (e.g. iron and magnesium) present. The volume of wastewater produced is directly influenced by the moisture content of the biomass, which is removed by evaporation during gasification.

During methanation, catalyst dust from the catalytic processes (e.g. Ni) can also end up in the water phase during the final product upgrading step (dryers). No information could be found in the literature on likely concentrations of metals from leached catalysts present in wastewater, but they are likely to be influenced by feedstock composition, methanation conditions, and catalyst type.

Further pollutants can be introduced into wastewater streams through the production of demineralised water, which is required for wet-scrubbing, WGS, pre-reforming, catalytic hydrogenation reactions, and cooling. The generation of demineralised water can produce waste in the form of brine.

Prior to discharge, wastewater can be treated using a variety of techniques as outlined in Section 4.13.1.

4.3.9 Emissions to air

During normal operations, the production of biomethane will not release emissions to air as production is within a closed system. Unintentional leakage of toxic gases into the atmosphere may occasionally occur during operations. This will be monitored using alarm-equipped gas detectors that monitor the concentration of toxic gases (such as H_2, CO, CH_4 and H_2S), and through appropriate control systems with defined ranges for such gases. The handling of leakage will be covered under standard operating procedures to keep the working environment safe and prevent unwanted toxic release to atmosphere. Abnormal operations such as emergency shutdown of plant or process shutdown may also require venting of biomethane or other gaseous by-products to a combustor/flare. This will produce a flue gas, mainly consisting of CO_2, that will be released to the atmosphere. A flue gas cleaning system is typically installed downstream of the combustor/flare to minimise the risk of the pollutants identified in Table 16 as arising during the gasification and downstream processes being emitted to air.

During maintenance and start-up there are specific procedures in place, depending on the plant design. If the design allows it, maintenance can take place while the process is warm to avoid operational disturbances. Normally, the installation (or the part of the installation under maintenance) is vented and purged with inert gases or diluted air.

Feedstock storage and pre-treatment pose the greatest risk of emissions to air during normal operations, as uncontained feedstock can emit fugitive air pollutant emissions during transport, storage and pre-treatment. The pollutants most commonly released during the transport and storage of gasification feedstocks are particulate matter. Degradation of biomass and biowaste feedstocks while they are in storage may also give rise to fugitive emissions of CO_2, CO and non-methane volatile organic compounds (He et al., 2014). However, best practice management of gasification feedstock typically involves contained transport and storage and can have a very high efficacy for emission reduction. For example, the use of fixed roof covers is reported to reduce emissions by 95–98% (European Commission, 2006).

Fugitive emissions of biomethane are possible at all stages of production and storage. However, detailed information on the scale of fugitive emissions from gasification and methanation is not available due to the relative commercial immaturity of the technology (Intergovernmental Panel on Climate Change, 2019).

4.3.10 Emissions to land

Impacts to land from gasification are most likely to result from the disposal of solid waste streams. The product gas from gasification processes contains various amounts of impurities and particulate matter originating from the solid feedstock and the bed material (Prabhansu et al., 2015). Alkali metals (potassium, sodium, calcium) are present in the biomass and, although they vaporise at high temperatures, they condense downstream during the heat recovery phase, leading to deposition on cooler surfaces downstream or the formation of PM (Prabhansu et al., 2015). To minimise this, cleanup technologies are included to remove particulates, which helps to lower concentrations of entrained solids in the syngas (National Energy Technology Laboratory, 2022).

Ash and PM are the primary solid waste streams generated in the ordinary operation of a gasification and methanation plant. Different fractions of ash are produced during gasification, such as fly ash and bottom ash. Fly ash includes boiler ash, cooler ash, cyclone ash and filter ash, which can contain high amounts of metals (e.g. calcium, potassium) (Liakakou et al., 2019). Bottom ash (slag, dry bottom ashes and bed solids) contains phosphorus and potassium, which can be recycled for agricultural use (Pels & Saraber, 2011). Ash is typically disposed of through landfilling; however, reuse applications such as an additive to cement or for soil amelioration may be possible (Guo et al., 2023). Biomass typically consists of plant material from the agricultural and forestry industry, as well as plant waste from the food industry. This makes biomass ash waste particularly difficult to characterise due to the large variability in chemical composition depending on the type of biomass and also the gasification technology used (Odzijewicz et al., 2022). Ash waste can be a valuable fertiliser (containing nutrients like calcium, potassium and other microelements), but may also contain leachable toxic compounds

including heavy metals, PAHs or volatile organic compounds (VOCs), in which case it is considered to be hazardous waste (Odzijewicz et al., 2022; National Energy Technology Laboratory, 2022).

4.4 E-methane via methanation

4.4.1 Process description

E-methane is generated via the methanation process, where a chemical reaction (known as the Sabatier reaction) converts carbon dioxide and hydrogen to methane. The main methanation technologies can be divided into catalytic and biological. The selection of methanation technology depends on the scale required, sources of H_2 and CO_2 available, process speed and energy requirements. Catalytic methanation is typically preferred for large-scale industrial production; it requires a constant flow of H_2 and CO_2 (ideally pure) and has high energy requirements and faster reaction times. This discussion focuses on the catalytic route, which is the more mature technology. Its TRL ranges from 7 to 9 (European Biogas Association, 2024b), depending on the setup: fixed bed reactors with Nickel catalysts are at TRL 8–9, while fluidised bed reactors are at TRL 7. The process is simple and includes production of the feedstocks CO_2 and H_2, followed by fuel synthesis and upgrading. The process diagram is presented in Figure 2.

In the biological route, microorganisms are used to convert CO_2 and H_2 to CH_4 and H_2O. This approach is typically applied to biogenic CO_2 sourced from AD plants, and the TRL can range from 4 to 8, depending on the setup (European Biogas Association, 2024b). For example, a tubular foam-bed reactor is at pilot-scale (TRL 4–5), while Biogasclean's commercial-scale Bio E-Fuel system is at TRL 8, as it is integrated into large biogas plants for CO_2 upgrading at scale. Other alternative novel technologies include bio-electrochemical assisted AD (TRL 4–5) and co-electrolysis of H_2O and CO_2 (TRL 4–6).

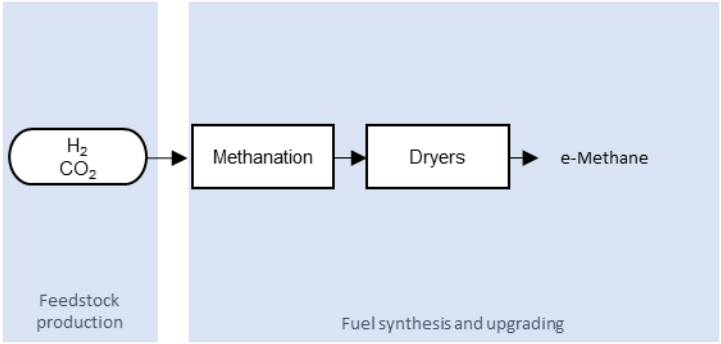

Figure 2. Process diagram for the production of e-Methane via Methanation

4.4.2 Feedstock production

The H_2 required for the process is generated via the electrolysis of water. There are various mature options for generating renewable power for the electrolysis (e.g. photovoltaic, wind, or hybrid power stations). The CO_2 required for the process can be categorised into three main types: biogenic, fossil and atmospheric CO_2. It can be captured through various methods, such as direct air capture (DAC) for atmospheric CO_2 or recovery from the flue gases of industrial processes for fossil or biogenic CO_2. In the latter case, the resulting stream often contains additional gaseous components. These

include water vapor, H_2, CO, N_2, O_2, CH_4, H_2S, SO_x, NO_x, particulate matter and others (Razak et al., 2023). The concentration of these components varies depending on the capture method used and the CO_2 source. Some of these components, such as CH_4, H_2S, SO_x and NO_x, must be removed before the CO_2 is introduced into the process, as they can lead to degradation of piping and process equipment, as well as catalyst poisoning.

4.4.3 Fuel synthesis and upgrading

The methanation reaction typically takes place in fixed bed reactors at moderate pressure (800-1000 kPa) and temperatures between 180 and 350°C. Higher pressure might increase methane yield but can also produce a greater number of by-products (such as higher hydrocarbons or solid carbon deposits on the catalyst that generate fouling) (Joint Research Centre, 2024). Typically, Ni-based catalysts are used for methanation, under the same reaction conditions as described in Section 4.3. More than one methanation reactor might be required to achieve full CO_2 conversion. The final step involves drying to remove the water formed during the methanation reaction.

E-methane production is currently at TRL 6–8, with 35 e-methane production plants operational as of the end of 2023 (Dell'Aversano et al., 2024). Key players include Hybridkraftwerk Limeco (Switzerland), P2X Solutions (Finland), e-gas ATLANTIS (Germany) and Biofactory Pau (France) (European Biogas Association, 2024b).

4.4.4 Pollutants generated through the production of e-methane by methanation

Table 17 summarises possible pollutant products generated during the process steps of e-methane production from catalytic methanation. However, during normal plant operation, e-methane production occurs within a closed system and therefore the risk of these pollutants being emitted to air or water pathways is minor. As discussed in Section 4.3.7, high operating pressures may create a risk for gas leakages, i.e. through pressure relief valves; however, operation is typically at moderate pressures of 800–1000 kPa. More details of the standard practices for preventing gas leakages are given in Section 4.4.6.

Table 17. Summary of possible pollutants from the e-methane production by the methanation process

Pathway	Production Step (Source)	Pollutants
Air	Feedstock production	During the CO_2 capture process, various components of the flue gas could end up in the CO_2 stream: CO, N_2, O_2, CH_4, H_2S, SO_x, NO_x, and PM.

Pathway	Production Step (Source)	Pollutants
	Fuel synthesis and upgrading	CH_4 [10], water (as steam), CO, H_2
Water	Feedstock production	Depending on the CO_2 capture process, liquid solvents used in the selected process (see Table 12) are considered as pollutants if there is a leakage.
	Fuel synthesis and upgrading	Wastewater from the final drying step, potentially contaminated with trace amounts of dissolved gases (CO_2, CO, H_2), catalyst degradation products.
Land	Unlikely to be any emissions to land	

4.4.5 Emissions to water

The predominant risks to the water environment result from the generation of wastewater during the methanation production step. During methanation, gaseous by-products such as CO_2, CO and H_2 may be entrained in wastewater, alongside catalyst dust from the methanation catalysts (e.g., Ni). These could end up in the water phase prior to the drying step. CO_2 is readily soluble in water, forming carbonic acid (H_2CO_3) and increasing the pH.

No information could be sourced from the literature on the concentration of metals from leached methanation catalysts present in wastewater. This is probably due to differences in methanation conditions and catalyst type.

Wastewater can be treated using a variety of techniques, as outlined in Section 4.13.1.

4.4.6 Emissions to air

The potential air impacts of e-methane production through catalytic methanation are similar to those associated with biomethane production via methanation. Under normal operations, both are produced in a closed system, with the concentration of gaseous toxic components being monitored via alarm detectors. Similarly, abnormal operations, such as emergency shutdowns or maintenance, may require venting or flaring of methane and

[10] Leakage of methane is possible during compression or storage.

other by-products such as CO. This can result in the gases identified in Table 17 being emitted to the atmosphere.

Feedstock production for e-methane consists of capturing CO_2 and producing renewable H_2, which can contribute to emissions from upstream processes. Fugitive emissions from carbon capture and storage systems can occur during the capture, compression, liquefaction and transportation of CO_2. As highlighted in Section 4.2.2, the various flue gas components which may leak during the CO_2 capture process include CO, N_2, O_2, CH_4, H_2S, SO_x, NO_x and PM. Best practice management of CO_2 capture can significantly reduce the risk of these components leaking into the atmosphere. Fugitive emissions from the renewable hydrogen production process depend on the electricity used. The transport and storage of hydrogen as a feedstock poses risks due to its flammability and potential indirect climate impacts. However, these risks can likewise be minimised through best practice management of storage and transportation.

As with biomethane, fugitive emissions of e-methane are possible at all stages of production and storage. However, since the supply chain is not fully commercially mature, no detailed data on the scale of these emissions is available.

4.4.7 Emissions to land

There is a scarcity of research on the impact of e-methane production on the terrestrial environment. There is potential for indirect risks related to wastewater, from chemical by-products of catalysts and improper catalyst disposal or leaks from the catalysts that could lead to soil contamination. Also, as methane is a tropospheric ozone precursor (photochemical oxidant), this could lead to reduced crop yields, because surface ozone has a significant negative impact on crops (Avnery et al., 2012). If carbon capture utilises industrial processes (for example where CO_2 is captured directly from the flue gas generated by power plants or other industries), there is a greater risk of contamination from these by-products, such as sulphur oxide particles (Yagihara et al., 2022).

4.5 Synthetic paraffinic kerosene via gasification and Fischer-Tropsch

4.5.1 Process description

Figure 3 presents a process diagram for the production of Fischer-Tropsch Synthetic Paraffinic Kerosene (FT-SPK) via biomass gasification. The TRL of the process is considered 7–8.

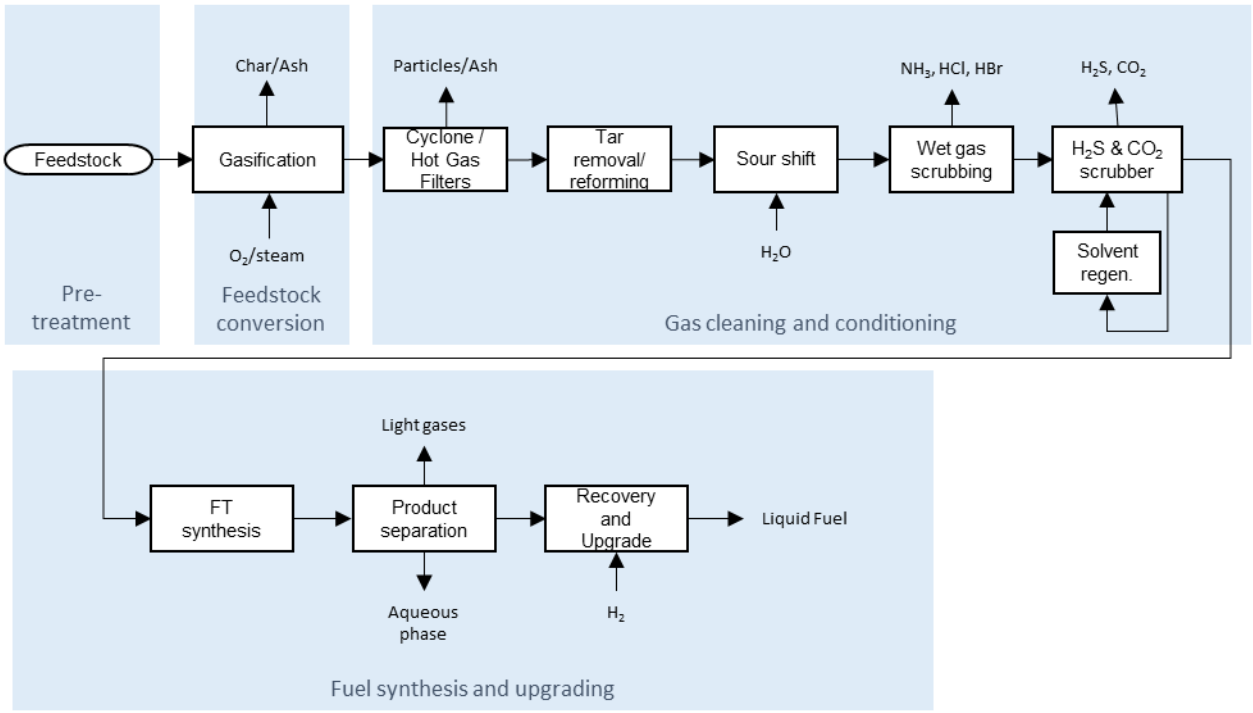

Figure 3. Process diagram for the production of Synthetic Paraffinic Kerosene by gasification and Fischer-Tropsch

4.5.2 Feedstock pretreatment

Feedstock pretreatment may be required to prepare the feedstock for the gasification process. The requirements for pre-treatment depend on both the type of feedstock (lignocellulosic biomass or waste feedstocks, like municipal solid wastes) and the chosen gasification technology. Pre-treatment processes are common to all gasification technologies, irrespective of the final fuel produced. Table 11 summarised the common pretreatment processes.

4.5.3 Feedstock conversion

The gasification process was described in Section 4.3. For FT synthesis, pure syngas (H_2 and CO, typically at a ratio of 2:1) is required rather than a product gas with a high methane concentration. For the feedstock conversion to pure syngas, typically high

temperature O_2/steam-gasification systems are preferred, as they produce a product gas with relatively low tar and hydrocarbon content.

4.5.4 Gas cleaning and conditioning

In the gas cleaning section of the process, PM/dust, which may contain alkali and heavy metals, is initially removed using the technologies described in Section 4.3.4. Hydrocarbons (tar, BTX and lighter hydrocarbon compounds) are typically converted by O_2/steam catalytic reforming or thermal reforming. The choice of technology depends on the specific plant configuration; for example, if O_2 is available on-site, O_2/steam catalytic reforming might be selected. Reforming of hydrocarbons, although an energy intensive process, can maximise the production of H_2 and CO in the product gas. VTT reported that almost complete conversion of tar and other hydrocarbons can be achieved, using a multistage catalytic reforming unit operated at elevated temperatures of 850–950°C (Kaisalo, 2017). Tar and C_2-hydrocarbons are decomposed first using zirconia and/or noble metal catalysts. This enables subsequent reforming in several stages with nickel and/or noble metal catalysts without problems caused by soot formation. However, for complete conversion of some stable components like methane, ammonia and benzene, high temperatures, large catalyst volumes and several catalyst stages are required (Hannula & Kurkela, 2013). The exact catalyst volumes depend on the tar content and composition of the product gas, the choice of reforming catalyst and the type of catalytic reactor. The catalyst volume is typically defined by the gas hourly space velocity, which is recommended by the catalyst supplier. The TRL for gas cleaning and conditioning ranges between 5 and 9. While FT-based conversion using non-renewable feedstocks is mature (TRL of 9), technologies integrating renewable sources have a lower technological maturity.

The other main impurities that need to be removed were described in Section 4.3.4 (and summarised in Table 12).

Some of the common gas conditioning processes downstream of gasification and gas cleaning were summarised in Table 14. However, different types of processes may be required, depending on the selected plant configuration, the specific technologies selected and the gas composition. Alternative gas conditioning processes that can be used in the FT-SPK via gasification are summarised in Table 18. For example, in some designs, it is more efficient to use the sour shift process with sulphur-tolerant catalysts prior to sulphur removal, instead of the normal WGS with catalysts that require sulphur-free gas (Hannula & Kurkela, 2013). This would minimise the number of units required but might not always be feasible, depending on the process conditions. More details on the different unit operations and their operating conditions can be found in Table 14. Following the sour shift, the gas is cooled to remove water and cleaned from sulphur and CO_2, typically using solvent-based processes like Rectisol or Selexol, as described in Section 4.3.4.

Table 18. Summary of the gas conditioning processes commonly used in the FT-SPK via gasification

Gas cleaning and conditioning process	Purpose
Sour shift	Utilises sulphur-tolerant catalysts (i.e. Cobalt) to catalyse the WGS reaction (conversion of CO and H_2O to CO_2 and H_2) and to convert carbonyl sulphide (COS) and other organic sulphur species to hydrogen sulphide (H_2S).
CO_2 and H_2S removal	Removes acid gases (CO_2 and H_2S) simultaneously.

4.5.5 Fuel synthesis and upgrading

The final step is fuel synthesis and final product upgrading. The syngas (consisting of H_2 and CO) is catalytically converted via the FT process at high pressure (2000-3000 kPa) and medium temperature using Co- catalysts operating at 210–240°C or Fe- catalysts operating at 250–270°C (Hannula & Kurkela, 2013; National Energy Technology Laboratory, 2022). The raw product from the FT synthesis is called syncrude and is a mixture of hydrocarbons, oxygenated compounds (e.g. alcohols, ketones, aldehydes) and water. The separation of syncrude involves a combination of cooling, phase separation and distillation. The hot reactor effluent undergoes stepwise cooling and phase separators. Initially the mixture is cooled to around 120°C, causing the heavier hydrocarbons (e.g. waxes, long-chain alkanes/olefins) to condense into an organic liquid phase, while lighter components remain in the gas phase. Further cooling to around 40°C causes condensation of the lighter components (C_4–C_6 hydrocarbons, water and dissolved oxygenates) into a liquid phase. This liquid phase, containing a light organic phase and an aqueous phase, is separated using phase separation. The lighter fractions (C_1–C_4) together with unconverted syngas are recycled back to the synthesis reactor (Hannula & Kurkela, 2013). The C_6 and heavier oil fractions are hydrocracked. For the hydrocracking step, operating temperatures are typically 290–425°C, with pressures of 800–10000 kPa over a bifunctional catalyst (de Klerk et al., 2024; Pleyera et al., 2020). The last step is distillation, to separate the different fractions. The aqueous product, containing the oxygenated compounds, is treated as wastewater.

4.5.6 Water abstraction requirements

Water abstraction requirements are the same as those described previously for biomethane via gasification and methanation, as neither the methanation nor FT process consumes water.

Regarding water requirements for on-site steam consumption, this is approximately 12.7kg/kg of FT product (Hannula & Kurkela, 2013); however, typically no additional water input is required as the steam production is generally a part of an integrated heat system.

Gross steam production is estimated as approximately 15.2kg/kg of FT product (Hannula & Kurkela, 2013).

4.5.7 Pollutants generated during the production of FT-SPK

A summary of all products generated during the different process steps of FT-SPK production from gasification is given in Table 19. Most of these products are classified as toxic compounds and thus considered pollutants. However, during normal plant operation, FT-SPK production occurs within a closed system, so the risk of these pollutants being emitted to air or water pathways during normal plant operation should be low. However, there may be a risk of release if venting or purging is required, or during maintenance. As in the biomethane production process from gasification (Section 4.3.7), most reactions take place in the gas phase, so there is a greater risk of gas leakages through pressure relief valves and gas cleaning operations. More details of standard practices for preventing this were discussed in Section 4.3.9. The risk of any of the feedstock impurities (such as S, N, alkali or heavy metals) ending up in the final fuel is minimal, as the catalysts used in the FT process are very sensitive to these impurities and require prior removal to prevent deactivation and to extend their lifetime and the process efficiency.

Table 19. Summary of possible pollutants from synthetic paraffinic kerosene production via gasification and Fischer-Tropsch

Pathway	Production Step (Source)	Pollutants
Air	Feedstock storage and pre-treatment	Particulate matter and various other pollutants depending on feedstock
	Gasification	CO, CO_2, H_2, CH_4, C_{2+} HCs, HCl, HF, H_2S, COS, NH_3, HCN, NOx, SOx Tar (including PAHs) and BTX Particulate matter Alkali and volatile heavy metals (As, Cd, Co, Cr, Cu, Hg, Pb, Se, Zn, Ti, V)
	Gas cleaning and conditioning	CO, CO_2, H_2, CH_4, C_{2+} HCs, HCl, HF, H_2S, COS NH_3, HCN, NOx, SOx Tar (including PAHs) and BTX Particulate matter Alkali and volatile heavy metals (As, Cd, Co, Cr, Cu, Hg, Pb, Se, Zn, Ti, V)

Pathway	Production Step (Source)	Pollutants
	Fuel synthesis and upgrading	CH_4, CO_2, CO, H_2
Water	Feedstock pre-treatment	Wastewater may be contaminated with dissolved organics, heavy metals or particulates[11]
	Gasification	-
	Gas cleaning and conditioning	Tar including PAHs, and BTX Inorganic salts of NH_3, HCl, HCN Metals: As, Cd, Co, Cr, Cu, Hg, Pb, Se, Zn, Ti, V Dissolved gases (CO, CO_2, CH_4), H_2S, COS, mercaptans Excess moisture from the process may be contaminated with metals from the catalysts
	Fuel synthesis and upgrading	Excess moisture from the process may be contaminated with metals from the catalysts. Some hydrocarbons and oxygenated by-products (alcohols, aldehydes, ketones, organic acids) might end up in the aqueous phase
Land	Unlikely to be emissions to land	

4.5.8 Emissions to water

Emissions to water from the following process steps are the same as those discussed for biomethane via gasification and methanation in Section 4.3:

- Gasification of feedstocks
- Gas cleaning and conditioning
- Generation of demineralised water

The Fischer-Tropsch process primarily converts syngas into hydrocarbon species such as n-paraffins and olefins. However, small quantities of oxygenates such as alcohols, aldehydes, ketones and organic acids may also be produced (Shafer et al., 2019). While

[11] If cleaning processes are used during pre-treatment.

these by-products are predominantly converted into hydrocarbons through isomerisation and hydrogenation reactions, as well as hydrocracking of longer chain hydrocarbons, some water-soluble organic compounds such as alcohols, ketones, acids and aldehydes will be present within the aqueous water phase produced during the FT reaction. Due to the high load of these VOCs within the FT wastewater, treatment is often required prior to discharge to wastewater treatment facilities. This is conducted with water distillation units, which separate out the volatile organic compounds from the wastewater, reducing the chemical oxygen demand of wastewater, and allowing for organic compounds contained within the wastewater to be reused for fuel production (Rahman et al., 2021). Any VOCs that cannot be recovered are removed through incineration, mitigating the risk of releases to air. Contamination from cobalt or iron catalysts may also occur due to leaching, as a result of their use in FT catalysts. The composition and concentration of these pollutants in the wastewater depend on the FT process conditions. Further techniques used to treat wastewater are outlined in Section 4.13.1.

4.5.9 Emissions to air

Emissions to air from the gasification of feedstocks and the removal of pollutants of the product gas during gas cleaning and conditioning are the same as those discussed for biomethane in Section 4.3.9. In summary, no emissions to air are anticipated under normal operations of gasification and FT crude upgrading to kerosene, with abnormal operations potentially resulting in emergency venting and flaring. The main risk from emissions to air occurs during transport and storage of the final kerosene fuel, and this can be minimised using best practice approaches. These approaches are the same as for conventional kerosene and are covered by Control of Pollution (Oil Storage) (England) Regulations 2001, which aim to minimise the risk of pollution incidents resulting from the storage of oil products (OTS advanced fuel storage systems, 2023). This legislation includes requirements for tank construction and maintenance, pipework and fittings, and labelling.

4.5.10 Emissions to land

As described in Section 4.3.10, emissions to land from gasification are most likely to result from the disposal of solid waste streams. In addition to ash (see Figure 3), char can be a solid waste stream generated in the gasification step during the production of FT-SPK. Char formation typically represents between 5 and 10% of the initial feedstock mass (Ahmad et al., 2023). Compositionally, char is composed primarily of unreacted carbon, with a small quantity of siliceous ash. The properties of gasification char are influenced by the gasification operating parameters such as temperature and biomass equivalence ratio (Ahmad et al., 2023). The produced char is typically burned in a combustor to produce heat for the process. Alternatively, similarly to ash, it can be disposed of through landfilling. One environmental assessment of the Fischer-Tropsch process concluded that the process does pose a risk in terms of terrestrial ecotoxicity (including plant toxicity and land pollution), but that the risk is relatively low (Rogachuk & Okolie, 2024).

4.6 Synthesised kerosene with aromatics derived by alkylation of light aromatics from non-petroleum sources

4.6.1 Process description

Figure 4 presents a process diagram for the production of synthetic paraffinic kerosene with aromatics via alkylation of light aromatics from non-petroleum sources (FT-SKA, also known as FT-SPK/A). This process is very similar to FT-SPK; the main difference here is that an additional aromatisation step is introduced, to add aromatics into the fuel composition, which allows higher blending percentages. The TRL of the process is considered 7–8.

Through alkylation, aromatic compounds are produced and blended into the fuel to provide a full spectrum of molecules found in typical petroleum-based jet fuel, rather than just paraffins. A minimum content of aromatics is required in jet fuels to ensure the swelling of jet engine seals. The aromatics can be introduced into the pathway externally or produced internally and added to the final fuel composition. These aromatics can be produced from different sources including light naphtha from coal tar (Sasol pathway), aromatisation of Fischer–Tropsch light products, catalytic cracking of Fischer-Tropsch heavy products, or a combination of the latter two processes (Greenfield global pathway) (de Klerk et al., 2024).

As a result, various FT-SKA pathways are possible. The coal tar pathway operated by Sasol is currently ASTM-approved but is unlikely to meet UK sustainability criteria. Therefore, this section describes the Greenfield global pathway, as shown in Figure 4.

4.6.2 Feedstock pretreatment

This step is the same as with the FT-SPK process, as pre-treatment processes are common to all gasification technologies, irrespective of the final fuel produced. A range of biomass and biowaste feedstocks can be used and Section 4.2 summarises the common pretreatment processes. The selection of feedstock is likely to depend on local resource availability and feedstock prices, as well as technical considerations (i.e. catalyst performance, gasification efficiency) (Eleanor et al., 2024).

4.6.3 Feedstock conversion

The gasification process is similar to that used in the FT-SPK process (Section 4.5.3). Syngas is produced, which then undergoes subsequent cleaning and conditioning for removal of impurities.

Where biomass is used under the Greenfield global pathway, aromatics are obtained by aromatisation of Fischer-Tropsch products (see Section 4.6.5). The processes commonly used are summarised in Section 4.6.5 and Table 20.

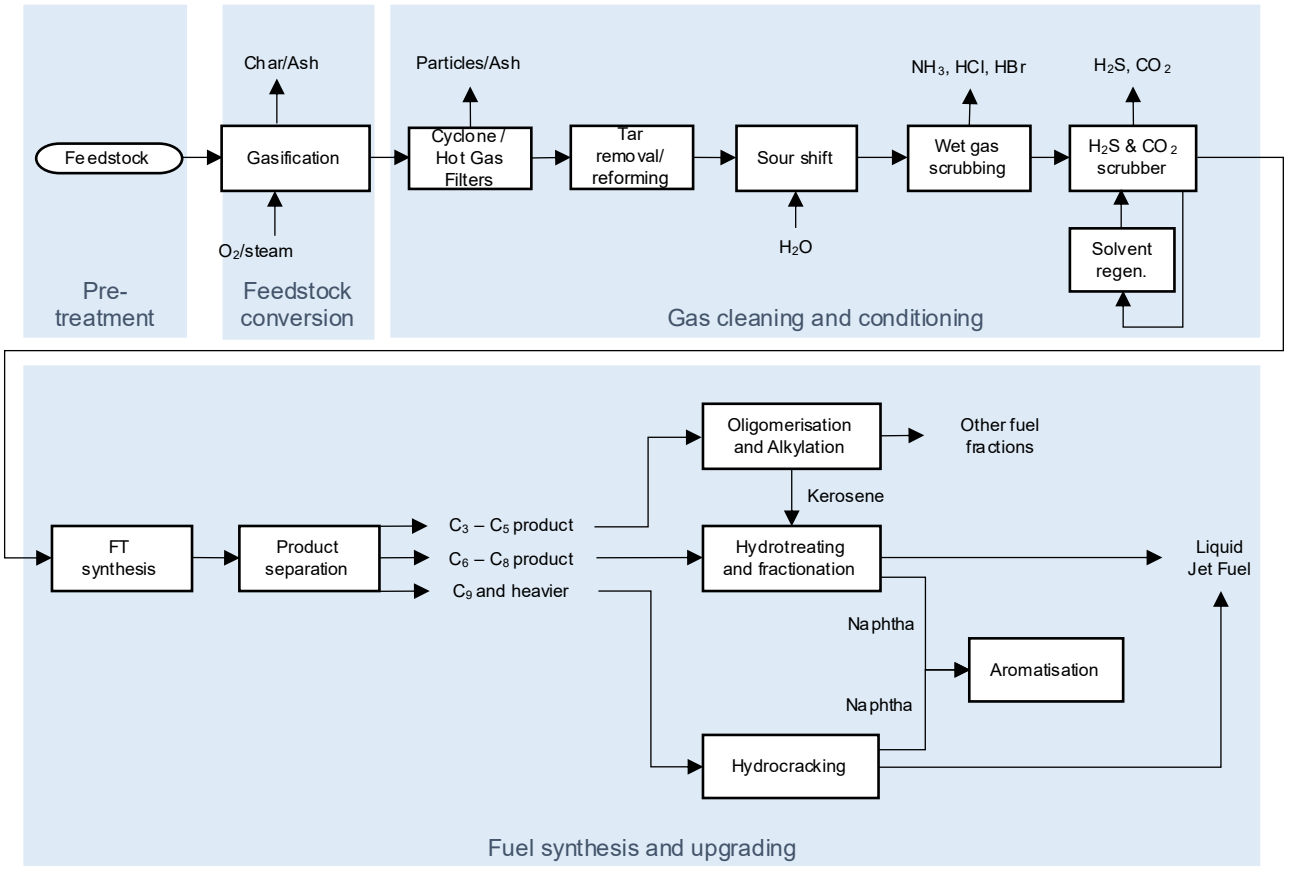

Figure 4. Process diagram for the production of Synthetic Kerosene with Aromatics via alkylation of light aromatics from non-petroleum sources (FT-SKA)

4.6.4 Gas cleaning and conditioning

This step is the same as with the FT-SPK process (see section 4.5.4 for more detail).

4.6.5 Fuel synthesis and upgrading

As with FT-SPK, the FT-SKA process undergoes FT synthesis and product separation, in order to convert the syngas to fuel (see section 4.5.5 for more details).

However, with FT-SKA, there is an additional step involving the alkylation of light aromatics (primarily benzene). Aromatics can be produced via the aromatisation of Fischer-Tropsch products; light FT products can be hydrotreated and fractionated to naphtha, and heavy FT products can be cracked to form naphtha, which can then undergo aromatisation. These aromatics can then undergo alkylation to produce kerosene range aromatics. A summary of the processes involved can be found in Table 20.

This process is approved under ASTM D7566, Annex A4 (ASTM, 2024). Sasol have developed an FT-SKA process with coal and Sasol employs the technology to blend its fully synthetic jet fuel (Radich, 2015). Rentech are also currently developing this process.

Table 20. Summary of the fuel synthesis and upgrading processes commonly used for FT-SKA production

Feedstock conversion process	Purpose
FT synthesis	Syngas (consists of H_2 and CO) is catalytically converted to straight chain hydrocarbons. Process conditions: high pressure and medium temperature (200–350°C, 2000–5000 kPa). Catalyst: Cobalt or iron-based (e.g., Co/SiO_2, Fe/Al_2O_3).
Product separation	Fischer Tropsch products are separated into desired fractions (i.e. naphtha, kerosene), via flash distillation and fractional distillation.
Aromatisation	Converts paraffins and olefins into aromatics via dehydrogenation and cyclisation. Process conditions: 400–600°C, 100–1000 kPa. Catalyst: Zeolite-based catalysts (e.g., ZSM-5, Pt/Al_2O_3).
Oligomerisation	Combines smaller olefins into longer-chain hydrocarbons. Process conditions: 150–300°C, 1000–5000 kPa. Catalyst: Zeolite or solid acid (e.g., H-ZSM-5, silica-alumina).
Alkylation	Combines aromatics (e.g., benzene) with olefins to form alkylated aromatics. Process conditions: 80–150°C[12], 1000–3000 kPa. Catalyst: Acid catalysts, such as HF, H_2SO_4 or zeolites (i.e. H-Y).[13]

[12] Lower temperatures are more common with homogeneous acid catalysts, while heterogeneous catalysts may operate effectively toward the higher end of this range.

[13] Solid catalysts (i.e. zeolites) are typically preferred, for simplifying catalyst handling, and reducing catalyst leakage into aqueous systems.

Feedstock conversion process	Purpose
Hydrotreating	Converts unsaturated hydrocarbons to saturated hydrocarbons, and removes impurities (e.g. sulphur, nitrogen), by hydrogenation and hydrodesulphurisation or denitrification respectively. Process conditions: 300–400°C, 2000–8000 kPa. Catalyst: Ni-Mo or Co-Mo on alumina.
Fractionation	Separation of different fuel fractions via a series of distillation operations, in order to extract jet fuel. Lighter fractions are usually recycled back to earlier stages (i.e. oligomerisation, aromatisation or alkylation steps) or used as feedstocks for other processes in the refinery. Heavier fractions may be cracked and recycled back to earlier steps or may be used in other processes in the refinery.

4.6.6 Water abstraction requirements

Water abstraction requirements for this process are comparable to the other conversion processes via gasification (see for example, section 4.5.6 on water abstraction requirements for FT-SPK via gasification).

4.6.7 Pollutants identified

The pollutants formed during FT-SKA are similar to those from FT-SPK (see Section 4.5.7). Table 21 summarises other pollutants from the additional steps involved.

Table 21. Summary of possible pollutants from FT-SKA production

Pathway	Production Step (Source)	Pollutants
Air	Oligomerisation	VOCs and light hydrocarbons
	Aromatisation	Hydrogen, light hydrocarbons, aromatic hydrocarbons (i.e. BTX)
	Alkylation	Minor unreacted olefins

Pathway	Production Step (Source)	Pollutants
	Hydrotreating	Hydrogen, hydrogen sulphide, ammonia[14]
Water	Oligomerisation	-
	Aromatisation	Aromatic hydrocarbons (i.e. BTX)
	Alkylation	Acid catalyst waste (e.g. HF, H_2SO_4)
	Hydrotreating	Aqueous phase (including S- and N-impurities)
Land	There are unlikely to be any emissions to land	

4.6.8 Emissions to water

There are potential impacts to water throughout the process of kerosene synthesis. The initial emissions to water (from feedstock to FT synthesis) are the same as for the FT-SPK process, as seen in section 4.5.

The aromatisation, alkylation and hydrotreating stages of synthesis carry some additional risks. During these stages, fractions of organic compounds from the FT process are converted to larger aromatic compounds and unsaturated bonds are saturated.

During these processes, organic compounds including aromatic hydrocarbons may be produced alongside trace metals from catalysts such as Ni-Mo or Co-Mo on alumina (used during hydrotreating). Acidic contaminants may enter the water phase from the acid catalyst waste during alkylation. A range of techniques can be used to treat wastewater, as detailed in section 4.13.1.

4.6.9 Emissions to air

The potential risks of impacts to air during FT-SKA are similar to those in the broader Fischer-Tropsch process and the refining steps used to produce fully formulated jet fuels, which typically involve separation by condensation, hydrocracking and the last step, distillation. As highlighted in section 4.6.5, however, these processes are conducted in closed systems and pose minimal risk during normal operations.

[14] If nitrogen impurities are present in the feedstock.

Some of the additional refining steps needed to produce FT-SKA from the FT product could generate air emissions. Aromatisation of light hydrocarbons to produce BTX uses platinum on chlorinated alumina catalysts. This process, similar to catalytic naphtha reforming, can release chlorine-containing compounds into the air (de Klerk et al., 2024).

Techniques such as flaring or thermal oxidation of waste gases (which combust VOCs to produce less harmful emissions like CO_2), scrubbing of process gases to remove pollutants such as SO_x, NO_x, and PM, and process optimisation are all used to mitigate potential air quality impacts.

4.6.10 Emissions to land

The impacts discussed relate to ash and char by-products (also discussed for biomethane production and FT-SPK in sections 4.3.10 and 4.5.10), which are produced prior to the aromatisation step. Although this ash could be used as a fertiliser, it may also contain toxic compounds harmful to the environment (e.g. polyaromatic hydrocarbons and volatile organic compounds) (Odzijewicz et al., 2022). When used in aeroplanes, FT fuels generally have fewer pollutants and are free of sulphur and nitrogen (Okolie et al., 2023), thus reducing the risk of contamination to land. However, the presence of aromatics in the fuel causes soot (or non-volatile PM) formation (Clean Air Task Force, 2023). Acidic contaminants (hydrofluoric acid and sulfuric acid) from the alkylation process could lead to land contamination risks if not stored or disposed of properly.

4.7 Synthetic paraffinic kerosene by alcohol-to-jet

4.7.1 Process description

Figure 5 presents a process diagram for the production of Synthetic Paraffinic Kerosene via the Alcohol-to-Jet process (AtJ-SPK). There are several potential variations of the process configuration, depending on the choice of feedstock.

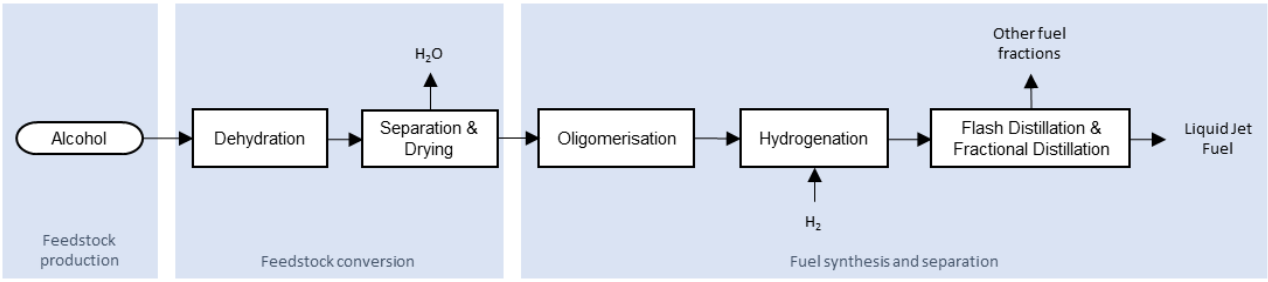

Figure 5. Process diagram for the production of Synthetic Paraffinic Kerosene via Alcohol-to-Jet

4.7.2 Feedstock production

The renewable alcohol feedstock (i.e. ethanol, butanol or isobutanol) can be obtained from the conversion of either starch and sugar-based[15] or lignocellulosic[16] biomass feedstocks. The biomass initially requires pre-treatment, after which it is hydrolysed to fermentable sugars. These sugars are then fermented to produce alcohols (Doliente et al., 2020). There can be various impurities present in the biomass which can carry through to the alcohol, depending on the biomass type.[17] Conventional sugar and starch-based feedstocks, such as sugarcane and wheat, will result in lower impurities than non-conventional sources, such as lignocellulosic sources. Additionally, the biomass pre-treatment process and fermentation process may also introduce contaminants. By-products can include: water, lignin, organic acids (i.e. acetic acid), furan-related compounds (i.e. furfural), sulphur-containing impurities (dimethyl sulphide and dimethyl sulfoxide) and fusel alcohols (i.e. isoamyl alcohol, n-propyl alcohol), or higher alcohols (Styarini et al., 2012; Habe et al., 2013).

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[15] Starch feedstocks are made up of complex sugars, and include corn and wheat. Sugar-based feedstocks are made up of simple sugars, and include sugarcane and sugar beet.

[16] Lignocellulosic feedstocks are non-food based feedstocks, such as agricultural residues, energy crops, and woody biomass.

[17] Based on the nature of the biomass, this may contain sulfur compounds, chlorinated compounds, nitrogen-containing impurities or minerals (i.e. potassium, sodium).

4.7.3 Feedstock conversion

The exact steps for feedstock conversion depend on the type of alcohol used as feedstock, i.e. ethanol, butanol or isobutanol. The feedstock can initially be converted via catalytic dehydration of alcohol to alkenes, i.e. ethanol can produce ethylene, or isobutanol can produce a mixture of butene isomers. This process produces large amounts of water, and potentially CO_2. Separation of these by-products is required, which can be undertaken via several steps.

The separation of alkene products from the reaction mixture can involve a combination of distillation, liquid-liquid separation, and molecular sieves, depending on the operating temperatures and pressures, and the design's performance (Geleynse et al., 2018). Table 22 includes some of the common separation steps for the AtJ-SPK process.

Table 22. Summary of the sequence of feedstock conversion steps for the AtJ-SPK process

Feedstock conversion process	Purpose
Dehydration	A catalytic reaction that converts the alcohols to alkenes, producing water and CO_2 as by-products. Catalyst: zeolites, alumina, or acid catalysts Reaction conditions: Moderate temperatures (e.g., about 250–350°C) and low pressures (e.g., 0–700 kPa) (Peters & Taylor, 2011).
Quenching	Purifies the alkenes by removing water and CO_2. Quenching process occurs with freshwater, followed by pressurising (to 2700 kPa, 15°C) to remove the CO_2
Caustic washing	Further removes CO_2 from the pressurised alkene gas, via bubbling it through NaOH.
Drying	A molecular sieve can be used as the final drying stage.

4.7.4 Fuel synthesis and separation

Following the formation of alkenes, the jet fuel is synthesised in a series of steps, as summarised in Table 23. Through oligomerisation, the alkenes are reacted over a heterogeneous acid catalyst (Peters & Taylor, 2011). This can then be hydrogenated / hydrotreated to saturate the double bonds, which can optimise the fuel properties. Once the hydrocarbon mixture is created, this can be separated into different fractions

(fractionated), to separate out the jet fuel fraction. The TRL of this process is at 7–8 (European Union Aviation Safety Agency, 2024).

Various fuel companies are currently developing and pursuing AtJ through the ASTM process. They include Byogy, Gevo, LanzaTech, Swedish Biofuels, Cobalt/USN and UOP. Commercialisation is being done by Gevo (butanol) and LanzaTech (ethanol). LanzaTech have successfully extended alcohol to jet conversion processes to include ethanol and increased the blend up to 50% to Jet-A. ASTM is reviewing the production of jet fuel from butanol and ethanol in addition to isobutanol, which has already been approved as AtJ-SPK (International Civil Aviation Organization, 2017).

Table 23. Summary of the fuel synthesis steps commonly used for the AtJ-SPK process

Fuel synthesis step	Purpose
Oligomerisation	To create long hydrocarbon chains from smaller alkenes Process conditions: 100–300°C, 2000–3500 kPa (Geleynse et al., 2018) Catalyst: acidic catalyst (i.e. alumina, zeolites)
Hydrogenation	The addition of hydrogen to convert the double bonded chains into single bond chains Process conditions: 250–450°C, 2000–10000 kPa Catalyst: bifunctional catalysts (Pt/Al_2O_3, Ni-Mo or Co-Mo on alumina)
Fractionation	Separate the hydrocarbon mixture into different fractions based on boiling point, i.e. jet fuel and other by-products. The jet fuel fraction typically boils in the range 150–250°C.

4.7.5 Water Abstraction Requirements

Water requirements for the AtJ-SPK process are outlined in Table 24. Fresh water is only required at the product quenching stage, with other requirements relating to utility systems only. A lot of water is produced at the initial dehydration stage of the AtJ-SPK process, and this can be treated to recycle it for use in the ethanol facility (Kourkoumpas et al., 2024). The literature indicates minimal cooling water requirements, probably due to the large volumes of water arising during the production process (Atsonios et al., 2015). One source indicates requirements of 0.02kg/kg of fuel (Romero-Izquierdo et al., 2021).

Table 24. Water abstraction requirements for the AtJ-SPK process[18]

Process step	Water abstraction requirement
Product quenching	Fresh water is required for product quenching[19] at the alkene purification stage.
Cooling-Systems	Water is required in cooling systems, such as the distillation step.
Heating-Systems	Water is required as steam for the initial dehydration step, as well as temperature for regulation in the reactors.

4.7.6 Pollutants generated through the production of AtJ-SPK

Table 25 summarises the products generated during the different steps of synthetic paraffinic kerosene production by AtJ that can be identified as possible pollutants (ZEMO, 2022). The risk of any of the feedstock impurities (such as S, N, alkali or heavy metals) ending up in the final fuel is unclear based on the published literature.

Table 25. Summary of possible pollutants from the AtJ-SPK process

Pathway	Production Step (Source)	Pollutants
Air	Feedstock production	Fugitive VOC
	Dehydration & separation	NOx, SO_2, CO, PM, CO_2, N_2O
	Oligomerisation	-
	Hydrogenation	Fugitive H_2
	Fractionation	NOx, SO_2, CO, PM, CO_2, N_2O, light hydrocarbons

[18] Limited information is available on the breakdown of water consumption for each process step.

[19] Quench water represents 80% of the waste generated at ethylene production facilities.

Pathway	Production Step (Source)	Pollutants
Water	Feedstock production	Water, lignin, organic acids and fusel alcohols (i.e. e isoamyl alcohol, n-propyl alcohol, n-butyl alcohol, isobutyl alcohol, sec-butyl alcohol, active amyl alcohol, and n-amyl alcohol), or higher order alcohols, dimethyl sulphide and dimethyl sulfoxide
	Dehydration & separation	Ethylene, ethanol, diethyl ether, acetaldehyde, wastewater (oil, organics, inorganic salts), spent NaOH[20] and catalyst degradation products (e.g., alumina dust or zeolite fines)
	Oligomerisation	Catalyst fouling residues (e.g., carbon deposits or coke), carbonaceous material and trace oxygenates if dehydration is incomplete
	Hydrogenation	Water, over-cracked products (e.g., light alkanes), gaseous hydrocarbons (e.g., methane, ethane, propane from cracking), light ends (e.g., naphtha, LPG fractions), sulphur, nitrogen, or oxygen compounds (from feedstock or incomplete catalyst cleanup), trace metals (leaching from catalyst, e.g., Ni or Co)
	Fractionation	Other hydrocarbon fractions (lighter/heavier), traces of oxygenates or unreacted alcohols (if not fully removed earlier), wastewater generated in the atmospheric distillation units (containing oil, H_2S, suspended solids, chlorides, organic compounds, ammonia, and the caustic soda used in column overhead corrosion protection)
Land	Unlikely to be any emissions to land	

4.7.7 Emissions to water

The AtJ-SPK process introduces potential impacts to the water environment through the generation of various wastewaters throughout the production process. Following the

[20] From the caustic washing step for CO_2 removal.

conversion of the alcohol feedstock to alkenes, excess water is removed through dehydration. This waste stream could contain unreacted feedstock (i.e., ethanol, butanol or isobutanol), as well as alkene products ineffectively separated out. The separation process to improve the purity of alkene products can also introduce waste pollutants into this wastewater stream, including degraded catalysts and NaOH.

A range of hydrocarbon species are produced during hydrogenation. Hydrocarbon byproducts (short chain hydrocarbons, LPG fractions, unreacted alcohols) are subsequently removed from the product stream and are combusted to generate heat for the process, are discharged as tail gas, or become entrained into wastewater. As outlined in previous sections, discharges to the aquatic environment can be mitigated through wastewater treatment, such as filtration, absorption and flocculation as detailed in section 4.13.1.

4.7.8 Emissions to air

The production and use of synthetic paraffinic kerosene by AtJ introduces potential air impacts due to emissions of pollutants such as NO_x, SO_2, CO and PM across its production stages. The alcohol feedstock can be obtained from the conversion of starch and sugar-based biomass feedstocks, or of lignocellulosic biomass feedstocks. In most cases the biochemical process for alcohol production is GHG- and energy-intensive, particularly for starches such as maize and cereals (Pavlenko & Searle, 2021).

As noted previously for other processes, the production of AtJ-SPK is conducted in a closed system and there is minimal risk of air impacts during normal operations. During the dehydration and separation stages, alcohol is converted to alkenes, producing water and CO_2 as by-products. Possible pollutants include NOx, SO_2, CO, PM, CO_2 and N_2O. The level of pollutants emitted depends on a variety of factors including the presence of sulphur in the feedstocks or the occurrence of incomplete combustion. There is possible risk of fugitive H_2 during the hydrogenation stage, linked to handling and storage; however, this can be mitigated by best practice.

4.7.9 Emissions to land

In comparison to conventional jet fuel, aromatics are absent from AtJ-SPK. Studies have also found that less soot is produced during combustion compared to conventional jet fuels as well as less particulate matter and sulphur (Okolie et al., 2023), which leads to less risk of land contamination. The biggest impacts are related to land use change caused by production of the renewable alcohol feedstock from biomass and potential changes in soil quality through nutrient loss and cultivation processes for the feedstock crops (Kourkoumpas et al., 2024). However, this impact is not applicable when lignocellulosic biomass is used as the feedstock to produce the alcohols. Unlike feed crops, lignocellulosic biomass – such as agricultural residues or forestry by-products – typically requires minimal land use changes and does not compete with food production. This reduces the environmental pressures associated with soil quality and land use change.

4.8 Synthetic paraffinic kerosene with aromatics by alcohol-to-jet

4.8.1 Process description

A process diagram for the production of synthetic paraffinic kerosene with Aromatics (AtJ-SKA) is presented in Figure 6.The process is very similar to AtJ-SPK (section 4.7) but includes an additional aromatisation step to add aromatics to the fuel, allowing the fuel to be blended with conventional kerosene up to 50% (ASTM, 2024).

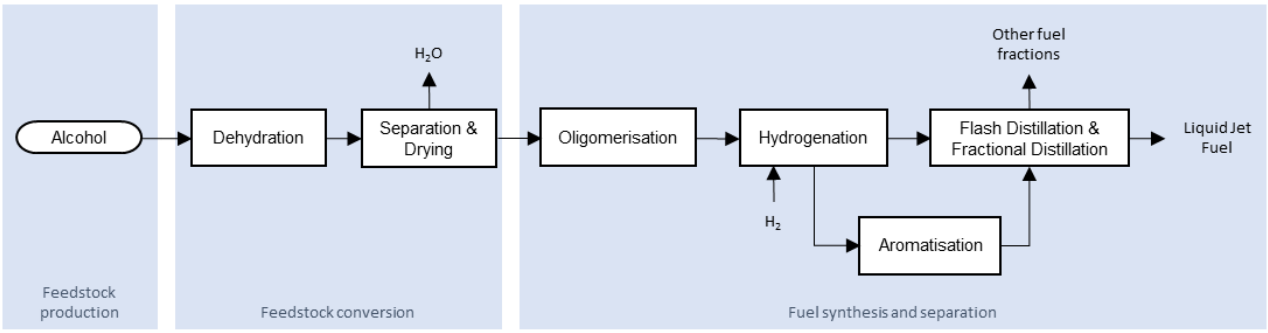

Figure 6. Process diagram for the production of synthetic paraffinic kerosene with aromatics (AtJ-SKA)

4.8.2 Feedstock production and feedstock conversion

These steps are the same as in the AtJ-SPK process and are described in section 4.7.1. The main feedstocks are C_2–C_5 alcohols (International Civil Aviation Organization, 2023).

4.8.3 Fuel synthesis and separation

As with the AtJ-SPK process, the fuel synthesis involves the oligomerisation of alkenes, followed by hydrogenation and then distillation to separate out the desired jet fuel fraction, (see section 4.7.4). However, for AtJ-SKA, the fuel synthesis stage also involves the formation of aromatics via cyclisation. This aromatisation reaction, following the hydrogenation step, is a catalytic reaction which converts a portion of the hydrocarbons into aromatic compounds. Typical catalysts used in this process are zeolites and the reaction occurs at high temperature (400–500°C) and pressure (1000–3000 kPa).

This process is currently ICAO-approved under ASTM D7566 Annex A8 (ASTM, 2024). It has a TRL of 7–8, with several companies aiming to scale up this process (IEA Bioenergy, 2024a). These include Byogy, Lanzatech and Swedish Biofuels (International Civil Aviation Organization, 2017).

4.8.4 Water abstraction requirements

Water abstraction requirements are the same as those described for AtJ-SPK (section 4.7.5), as the additional aromatisation step does not consume water.

4.8.5 Pollutants identified

As most of the processes for AtJ-SKA are the same as those for AtJ-SPK (see section 4.7.6), the same pollutants can be expected.

4.8.6 Emissions to water

Emissions to water from the feedstock production and conversion processes for AtJ-SKA are the same as those discussed for AtJ-SPK. Most pollutants introduced into wastewater streams relating to fuel synthesis and separation are also similar to those arising from the AtJ-SPK process due to comparable process steps (i.e., oligomerisation, hydrogenation and fractionation). An additional pollutant is the light aromatics (i.e. BTX) produced in the aromatisation step. More information on wastewater treatment techniques can be found in section 4.13.1.

4.8.7 Emissions to air

The impacts to air of AtJ-SKA are similar to those associated with AtJ-SPK as described in section 4.7.8.

4.8.8 Emissions to land

The impacts to land are similar to those for AtJ-SPK; however, where aromatic compounds are added to improve the fuel properties, aromatic hydrocarbons (for example benzene) are produced. These are toxic and can be hazardous to the environment. However, studies on rats found there to be limited toxicity differences to standard jet fuels (Mattie et al., 2023) (moderate irritation from inhalation and no change in reproductive health), suggesting that control measures similar to those for standard jet fuels could reduce the pollution risk to biodiversity. As with AtJ-SPK, the biggest impacts are related to land use change caused by the production of the renewable alcohol feedstock created from biomass (Kourkoumpas et al., 2024). However, this impact is not applicable when lignocellulosic biomass is used as the feedstock to produce alcohols.

4.9 Sustainable aviation fuel or diesel via pyrolysis

4.9.1 Process description

A process diagram for the production of fuels via pyrolysis is presented in Figure 7. The main products of this process are typically diesel and naphtha, but SPK aviation fuel and diesel production is possible if the process conditions are adjusted. There are many potential variations of the process configuration, depending on the feedstock and pyrolysis technology selected. However, the general process steps are common and include feedstock pre-treatment, feedstock conversion, product separation, and fuel upgrading.

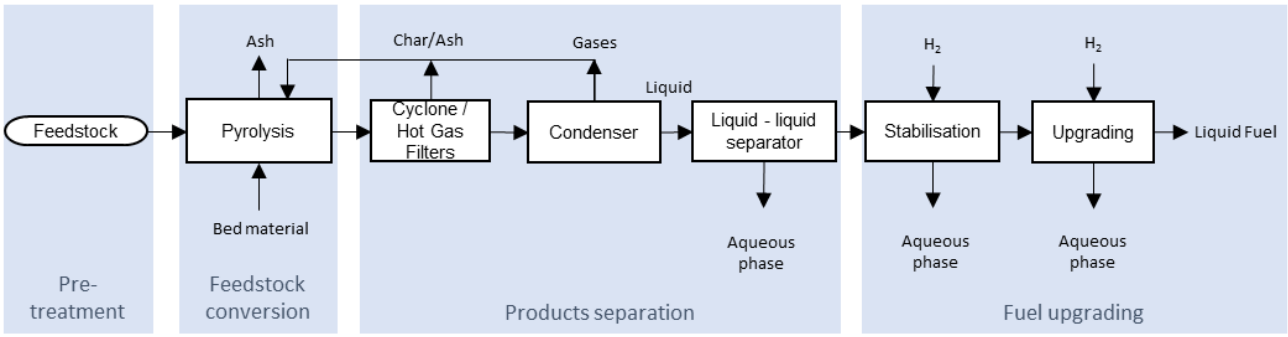

Figure 7. Process diagram for the production of sustainable aviation fuel or diesel via pyrolysis

4.9.2 Feedstock pretreatment

Feedstock pretreatment may be required to prepare the feedstock for the pyrolysis process. The exact requirements for pre-treatment depend on both the type of feedstock (e.g., biomass or waste) and the chosen pyrolysis technology (Jahirul et al., 2012). Common pretreatment processes for pyrolysis are similar to gasification and are summarised in Table 11 and in section 4.2.2. Depending on the type of the feedstock and pyrolysis technology, further pretreatment including milling and grinding of the feedstock to reduce the particle size and increase its reactivity might be required (Kargbo et al., 2021). For instance, feedstock for fast pyrolysis requires drying to below 10 wt% water content, while for flash pyrolysis it is important to mill and grind the feedstock to a particle size of 0.05-2mm, to ensure an appropriate residence time (Jerzak et al., 2024).

4.9.3 Feedstock conversion

Pyrolysis is a thermochemical process that converts carbon-containing feedstocks at elevated temperatures (300–600°C) and atmospheric pressures, into three main products: liquid (pyrolysis oil), solid (char/ash) and gas (pyrolysis gas). The relative quantities of these products and their composition depend on many factors, such as the feedstock, the pyrolysis technology, temperature, heating rate and residence time.

Different pyrolysis technologies are available on the market. Fast pyrolysis, using a high heating rate, is mainly used to produce liquid (known as pyrolysis oil or bio-oil). During fast pyrolysis, the biomass is mixed with a bed material (typically sand) in the pyrolysis reactor in the absence of oxygen. The produced char and bed material are recycled to a combustor where the char is burned to reheat the sand. The bio-oil produced consists of a complex mixture of 300–400 oxygenated compounds. It includes functional groups like carbonyls, carboxyls, and phenolics. The exact composition depends on many factors, such as the feedstock, the pyrolysis technology and the reaction conditions (Jahirul et al., 2012).

Fast pyrolysis technology has matured recently with the construction and operation of several commercial scale (TRL 8–9) installations using clean wood residue as feedstock, while the conversion of residual biomass streams and wastes is still at a lower TRL (van de Beld & Leijenhorst, 2024). The main use of the bio-oil produced to date has been for heat and power generation. The integration of this technology for the production of drop-in fuels remains a challenge due to limited commercial knowledge of the upgrading processes (TRL 4–5) (Kargbo et al., 2021).

4.9.4 Products separation

Pyrolysis product separation involves several process steps, as described in Table 26.

Table 26. Summary of the product separation processes commonly used downstream of pyrolysis

Product separation process	Purpose
Cyclone/Hot Gas Filters/Electrostatic Precipitators	Removes PM, char, dust (unburned carbon and ash), alkali and heavy metals. Some heavier condensing tar compounds can be removed as well.
Condenser	The vapours leaving the reactor are rapidly cooled in the condenser to 65–85°C, yielding pyrolysis oil and gases. The gases and surplus heat from the combustor can be used to generate steam for power generation, biomass drying or external use. The pyrolysis oil yield is about 50–75 wt% of the feedstock and includes a high water content (often in the range of 20–30%). If direct condensers are used (e.g. spray towers), a solvent is used to cool the vapours and remove H_2S, HCl or volatile inorganic vapours.

Product separation process	Purpose
Liquid-liquid separator	Phase separation between the oil fraction and the water fraction. Additional water may be required to achieve phase separation. The process produces a wastewater steam that contains some water-soluble organic compounds, such as phenols, ketones, aldehydes and esters, and an organic phase containing about 25 wt% water (Chuanyong et al., 2015). The aqueous phase can be reformed in a catalytic steam reformer for H_2 production. The organic phase (untreated pyrolysis oil) sometimes requires further filtration via cyclones or hot gas filters, to remove any PM/dust.

4.9.5 Fuel upgrading

The untreated pyrolysis oil is a complex mixture of oxygenated species (such as water, carbohydrates, carboxylic acids, phenols). Its high viscosity, acidity and water content lead to instability of the oil during storage and handling, so immediate upgrading is required. The bio-oil may be upgraded using existing infrastructure in a conventional refinery or in a stand-alone unit. The route chosen is likely to depend on the properties of the produced bio-oil, the scale and business case of the individual plant, and whether they want to invest in upgrading facilities.

Where existing refinery infrastructure is used, the bio-oil is blended directly with fossil vacuum gas oil (5–20 wt%) for upgrading in a catalytic cracker unit. Following this, it can be further upgraded (stabilised and hydrotreated), which will allow it to be blended at higher concentrations. Alternatively, the bio-oil can be fully upgraded in a stand-alone unit to produce a transportation fuel. Fuel upgrading aims to reduce the oxygen content of the bio-oil to produce a mixture of heavy, medium and light hydrocarbons, which can then be distilled into various fractions such as diesel, jet fuel and/or gasoline. This standalone upgrading process involves several steps, as described in Table 27. This description is based on the BTG bioliquids process (BTG bioliquids, 2024).

Table 27. Summary of the fuel upgrading processes used for producing SAF or diesel from pyrolysis oil

Upgrading process	Purpose
Stabilisation	This is a mild hydrotreatment process to improve the quality of the liquids by de-functionalising the oxygen present in the carbohydrates and to transform them to – preferentially – alcohols. This is a catalytic process, using Ni-Cu based catalyst at high pressure (20000 kPa) and temperature (100–300°C) under H_2 atmosphere. This process produces an aqueous phase that contains some water-soluble organic compounds, such as short chain alcohols, and can be reformed in a catalytic steam reformer for H_2 production.
Hydrodeoxygenation (HDO)	This is a deep hydrotreatment process to remove most of the oxygen from the stabilised bio-oil. It is a catalytic process, using HDO-NiMo or CoMo catalyst at high pressure (13000 kPa) and temperature (300–400°C) under H_2 atmosphere. Hydrotreatment also converts organic N and S contaminants to NH_3, N_2 and H_2S, respectively. This process produces an aqueous phase that contains some water-soluble organic compounds and can be reformed in a catalytic steam reformer for H_2 production.
Hydrogenation	The process further hydrogenates the deoxygenated pyrolysis oil in order to increase the H/C ratio and remove more oxygen. This is also a catalytic process that uses a NiMo or CoMo catalyst at high pressure (5000–10000 kPa) and temperature (300–400°C) under H_2 atmosphere. Different fuel ratios can be produced based on the reaction conditions (more severe cracking of the longer chain carbon molecules is required for SAF production than for diesel). This process produces an aqueous phase that still contains some water-soluble trace organic compounds and can be reformed in a catalytic steam reformer for H_2 production.
Distillation	Separates the different fuel fractions.

4.9.6 Water abstraction requirements

There are no process water requirements for the fuel synthesis and upgrading stages of production of SAF/Diesel by pyrolysis. Water will be required for heating and cooling utilities (i.e. reactor temperature regulation, distillation condenser). The literature indicates cooling water requirements of 3 litres of water per litre of product (Jones et al., 2009); however, it is noted that this requirement can be reduced by optimisation of the quench process.

4.9.7 Pollutants generated during the production of SAF/ diesel via pyrolysis

Table 28 summarises the products generated during the different process steps of SAF/Diesel via pyrolysis that were identified as possible pollutants. However, during normal plant operation, fuel production is within a closed system, so the risk of these pollutants being emitted to air or water pathways is minor. The risk of any of the feedstock impurities (such as S, N, alkali or heavy metals) ending up in the final fuel is unclear based on the published literature.

Table 28. Summary of possible pollutants from SAF or diesel production via pyrolysis and upgrading

Pathway	Production Step (Source)	Pollutants
Air	Feedstock storage and pre-treatment	Particulate matter and various other pollutants depending on feedstock
	Pyrolysis	CO, CO_2, H_2, CH_4, C_{2+} HCs, HCl, HF, H_2S, COS, NH_3, HCN Tar (including PAHs) and BTX Particulate matter Alkali and volatile heavy metals: As, Cd, Co, Cr, Cu, Hg, Pb, Se, Zn, Ti, V
	Products separation	CO, CO_2, H_2, CH_4, C_{2+} HCs, HCl, HF, H_2S, COS, VOC, NH_3, HCN Tar (including PAHs) and BTX Particulate matter Alkali and volatile heavy metals: As, Cd, Co, Cr, Cu, Hg, Pb, Se, Zn, Ti, V

Pathway	Production Step (Source)	Pollutants
	Fuel upgrading	VOC, NH_3, H_2S
Water	Pyrolysis	-
	Products separation	Tar including PAHs, and BTX Metals: As, Cd, Co, Cr, Cu, Hg, Pb, Se, Zn, Ti, V Dissolved Gases (CO, CO_2, CH_4), H_2S, COS, mercaptans Aqueous phase containing water-soluble organic compounds
	Fuel upgrading	Aqueous phase containing water-soluble organic compounds that can be contaminated with trace metals (such as Ni, Co, Mo, Cu) from the catalysts
Land	Unlikely to be any emissions to land	

4.9.8 Emissions to water

Water-soluble organic compounds arise during the separation of the aqueous phase and the organic liquid product following conversion of the pyrolysed feedstock, and from fuel upgrading, e.g., stabilisation, hydrodeoxygenation and hydrogenation. Wastewaters may contain a variety of organic compounds from pyrolysis oil and contact with organic phase intermediates. Soluble gases present in the feedstock, or generated as a byproduct, can also dissolve in condenser water, or aqueous phases produced during phase separation and product upgrading.

Heavy metals may also be present from feedstock impurities, as mentioned in Table 10, or may be introduced from catalysts leaching during production. Unwanted distillate fractions (e.g., short chain hydrocarbons, LPG fractions) removed from the product stream are discharged as tail gas or can become entrained into wastewater. Discharges to the aquatic environment can be mitigated through the best available techniques for wastewater treatment. Treatment options include, for example, filtration, adsorption, and flocculation (Joint Research Centre: Institute for Prospective Technological Studies, 2016). More details are provided in section 4.13.1.

The composition and concentration of pollutants contained within wastewater streams depends on process conditions (i.e. temperature, pressure, residence time, and catalyst choice) as well as the choice of feedstock (Han et al., 2019).

4.9.9 Emissions to air

As noted previously, during normal plant operation, fuel production is within a closed system, so the risk of these pollutants being emitted to air or water pathways is minor. Different pyrolysis technologies and feedstocks influence the composition of pyrolysis products, as stated in section 4.9.7. Research indicates that VOCs present in pyrolysis gas increase concurrently with operating temperature (Pivato et al., 2024). There is a risk of fugitive VOC emissions from seals and flanges in tanks, pipework, and vessels, with some potentially being released from pressure relief valves.

4.9.10 Emissions to land

Impacts to land are most likely to result from the disposal of solid waste streams, namely ash and char (as discussed previously). Pyrolysis can lead to biochar production, which could be used to sequester carbon in soil (Geissler & Maravelias, 2022); however, biochar in general has not been proven to have a consistent impact on yield or soil stability. In fact, depending on source material, it may have an effect on pesticides and could show signs of toxicity to crops (Tisserant & Cherubini, 2019).

4.10 Sustainable aviation fuel or Diesel via Hydrothermal Liquefaction

4.10.1 Process description

Hydrothermal liquefaction (HTL) is particularly suited for processing wet biomass feedstocks, as it eliminates the need for drying. Wet biomass feedstocks, which can have moisture contents of up to 80%, include sewage sludge, manure, and macro- and microalgae biomass residues (Kargbo et al., 2021). Such wet residues are typically available at low cost.

Figure 8 presents a process diagram for the production of SAF/Diesel via HTL.

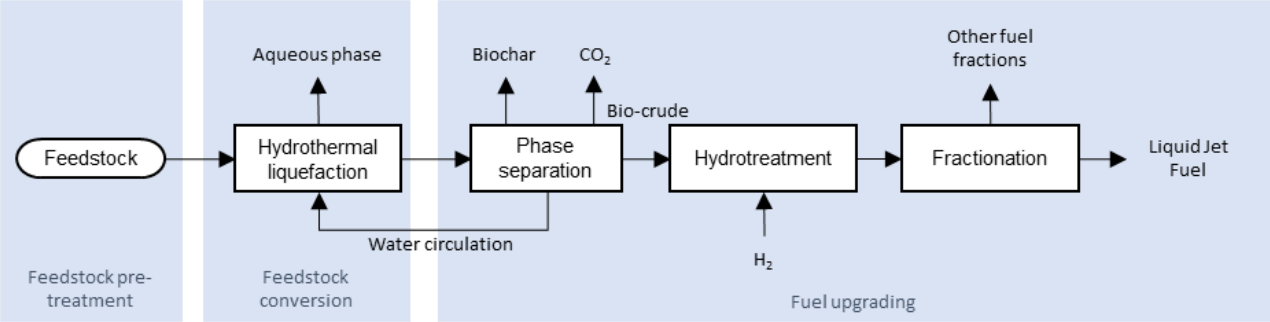

Figure 8. Process diagram for the production of SAF or diesel via Hydrothermal Liquefaction

4.10.2 Feedstock pre-treatment

For feedstocks like microalgae, pretreatment is generally minimal due to the small particle size, which simplifies pumping the feedstock slurry to the reactor. Dewatering during harvesting typically produces a slurry with around 20% solids, which is then fed into the HTL reactor. In contrast, lignocellulosic biomass may require more preparation steps, such as size reduction (as described in section 4.2) to address the complexities associated with its structure, and alkaline treatment to remove contaminants and obtain a stable slurry for easy pumping (Gollakota et al., 2018).

4.10.3 Feedstock conversion synthesis

The feedstock undergoes HTL under high pressures (5000–25000 kPa) and moderate temperatures (250–550°C) (Kargbo et al., 2021) to produce a bio-crude, solid residues (biochar), aqueous phase and gaseous products (mainly CO_2). The use of catalysts is not yet well established, with the catalyst effects varying by feedstock type. However, alkali and transition metal catalysts have generally been found to increase efficiency (Usman et al., 2024).

4.10.4 Fuel upgrading

The biocrude requires upgrading in a series of steps, summarised in Table 29, in order to produce the SAF/Diesel. The bio-crude may also be co-processed with petroleum fractions in conventional refineries.

The aqueous phase/water from the phase separation step can be recirculated to the HTL unit, which reduces the water requirement and enhances the biocrude yield. The other water stream that is generated from the HTL process can be treated anaerobically or via catalytic hydrothermal gasification techniques to produce methane-rich or hydrogen-rich syngas.

Research indicates that biocrude derived from sewage sludge exhibits desirable fuel properties after upgrading, although its high nitrogen content remains a challenge, necessitating additional denitrification (Cronin et al., 2022).

Table 29. Summary of the fuel upgrading steps commonly used downstream of the HTL process

Fuel upgrading step	Purpose
Phase separation	To extract biocrude from the aqueous phase, solid residue (biochar) and gaseous products (mainly CO_2).
Hydrotreating	Converts biocrude into fuel-range hydrocarbons, via hydrogenation. This can also remove oxygen, nitrogen and sulphur compounds as well as other impurities. Process conditions: 300–450°C, 5000–20000 kPa. Catalyst: Cobalt and Nickel based (e.g. CoMo/ Al_2O_3, NiMo/Al_2O_3) (Dimitriadis & Bezergianni, 2024).
Fractionation	The upgraded oil is distilled into desired fractions such as SAF and diesel.

There are various demonstration-scale HTL plants at TRL levels of 6–7 (IEA Bioenergy, 2024a). Examples include Canfor-Licella Joint Venture (Canada), Arbios Biotech (Australia) and SLUDGE2FUEL (Denmark).

4.10.5 Water abstraction requirements

Water is required for numerous process steps involved in the production of SAF or diesel via HTL. These are summarised in Table 30.

Table 30. Water abstraction requirements for SAF or diesel production via the HTL process[21]

Process step	Water abstraction requirement
Feedstock pre-treatment / cleaning	Freshwater is required to wash/clean feedstock and remove impurities
Moisture adjustment (dependent on feedstock)	Biomass needs to have sufficient water content for effective liquefaction (60–85%), so water may be required depending on the moisture content of the feedstock.
Cooling and heating systems	Water is required in cooling systems and heat-exchangers to regulate temperature and act as a condenser.

The predominant source of water required during SAF/Diesel production via hydrothermal liquefaction is as a reactant and solvent for the conversion of biomass to biocrude. Fresh, distilled water is typically used, but the use of seawater or industrial wastewater has been researched and may be feasible. In practice, the use of seawater may require adaptation to the process, while industrial wastewater would potentially require pre-treatment to remove negative impurities, although its high organic content may be favourable for the process (Harisankar et al., 2024).

The hydrogen used in hydroprocessing can also elevate water consumption, with the extent depending on the hydrogen production method employed, such as steam reforming or water electrolysis.

The production of fuel from the hydrothermal liquefaction of algae required 134L of water per megajoule (MJ) of energy-equivalent diluent, with over 99% attributed to biomass production. Of this, however, only 0.20 L/MJ diluent was attributed to biomass conversion and hydroprocessing steps (Nogueira Junior et al., 2018). Overall, the consumption of water for SAF/diesel by hydrothermal liquefaction will vary extensively based on numerous factors including the choice of biomass feedstock, water recycling processes, the agricultural system, and process conditions.

[21] Limited information is available on the breakdown of water consumption for each process step.

4.10.6 Pollutants identified

Pollutants formed during the HTL process are similar to those from FT-SPK, as described in section 4.5.7. Table 31 summarises the additional pollutants from the additional steps involved. The risk of any of the feedstock impurities (such as S, N, alkali or heavy metals) ending up in the final fuel is unclear based on the published literature.

Table 31. Summary of possible pollutants from SAF or diesel production via hydrothermal liquefaction

Pathway	Production Step (Source)	Pollutants
Air	Feedstock conversion	Ammonia, CO_2, CH_4, H_2 and other light gases, solid char, tars
Water	Feedstock conversion	Trace metals, organics (e.g. acetic acid, phenols, alcohols), salts, and nitrogen compounds
	Fuel upgrading	Ammonia, phenolic compounds, dissolved salts (i.e. phosphates, nitrates)
Land	Unlikely to be any emissions to land	

4.10.7 Emissions to water

Impacts to water occur from wastewater generated during feedstock pre-treatment (drying or cleaning) and phase separation. Wastewater can be contaminated with water-soluble organics, heavy metals from catalyst leaching, salts and nitrogen compounds. Soluble gases (e.g., CO_2 or NH_3) generated during fuel synthesis can also dissolve into aqueous phases. CO_2 can react with water to produce carbonic acid (H_2CO_3), lowering the pH. Unwanted distillate fractions (e.g., short chain hydrocarbons) removed from the product stream are discharged as tail gas or can become entrained into wastewater. Techniques for wastewater treatment are discussed in section 4.13.1.

4.10.8 Emissions to air

The potential risk of impacts to air from HTL occur from off-gassing and from stripping the HTL aqueous phase.

The off-gas during HTL is composed of 92% CO_2 and 8% C1-C5 gases. About 20% of the heat needed for the HTL reactor can be provided by burning this off-gas; however, the off-gas may require scrubbing, depending on local legislation.

After separation from the biocrude product, the HTL aqueous phase can be recycled back to the wastewater treatment plant. Ammonia content in the aqueous phase needs to be

reduced prior to discharge from the plant, as it can cause toxicity. This risk is reduced through the use of air stripping, where lime (CaO) is added to the aqueous phase to raise the pH and shift the equilibrium of NH_3/NH_4 to the gas phase. The effluent water is then brought into contact with air in a packed tower, which strips ammonia gas from the wastewater (Georgiou et al., 2019). The resultant ammonia/air stream from the air stripping process may contain VOCs at levels which are too high to recover a marketable ammonia product. A thermal oxidation unit is used to treat the ammonia/air stream and reduce the risk of volatile oxygenates. Ammonia and organics are catalytically combusted to N_2, CO_2 and H_2O and released to the atmosphere (Pacific Northwest National Laboratory, 2017). The main pollutants of concern are ammonia and VOCs through fugitive emissions, with VOCs contributing to the formation of smog; however, the treatment of the ammonia/air stream minimises this risk.

4.10.9 Emissions to land

Impacts to land are most likely to result from the disposal of solid waste streams, namely biochar (and the possible contamination therein), as discussed in Section 4.9.10 for the pyrolysis process.

4.11 e-Diesel via Fischer-Tropsch

4.11.1 Process description

Figure 9 presents a process diagram for the production of e-diesel via Fischer-Tropsch. The general process steps include feedstock production, gas conditioning, and fuel synthesis and upgrading. Although individual processes in the e-diesel production pathway are at TRL 8–9, the Reversed Water Gas Shift (RWGS) process is still at a low TRL level (6). Thus, it will impact the overall TRL of the integrated process.

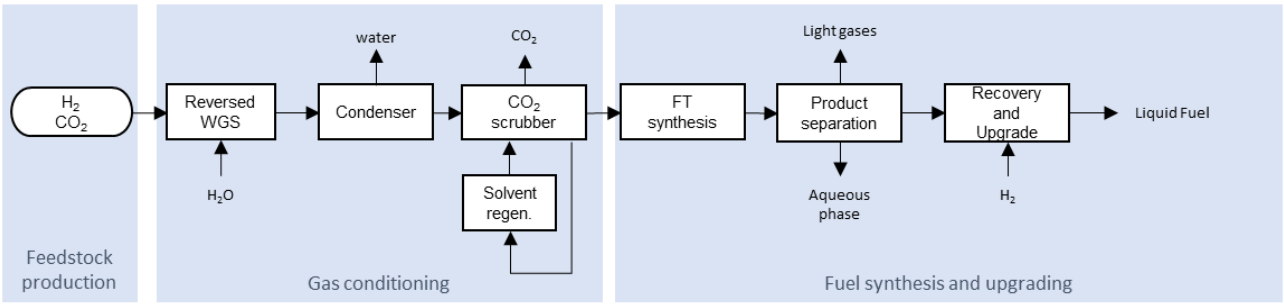

Figure 9. Process diagram for the production of e-Diesel via Fischer-Tropsch

4.11.2 Feedstock production

The feedstock for e-diesel production consists of hydrogen and carbon dioxide, as described in section 4.4.2. The scaling of e-fuel production is constrained by the availability and maturity of renewable energy, green hydrogen production, and carbon capture technologies. The H_2 required for the process is generated via electrolysis of water. CO_2 can be captured through various methods, and the resulting stream often contains additional gaseous components like water vapor, H_2, CO, N_2, O_2, CH_4, H_2S, SO_x, NO_x, PM and others. The composition of these components varies depending on the capture method used and the CO_2 source. Some of these components, such as CH_4, H_2S, SO_x and NO_x, must be removed before the CO_2 is captured and introduced into the process, as they can lead to catalyst poisoning and reactor degradation (Razak et al., 2023).

4.11.3 Gas conditioning

Gas conditioning involves several process steps, as described in Table 32.

Table 32. Summary of the sequence of gas conditioning processes commonly used for e-diesel production

Product separation process	Purpose
Reversed Water Gas Shift (RWGS)	Converts CO_2 to CO by reacting with H_2. This is a catalytic process, under noble metals (Pt, Pd, Rh, Ru, Au), as well as Fe, Mo, Co, Cu, and Ni-based catalysts. High temperatures (800–1000°C) and pressures (100–1000 kPa) are required to favour the equilibrium to CO.
Condenser	The syngas leaving the reactor is cooled in the condenser to remove the water from the gas.
CO_2 scrubber	Removes CO_2, using one of the methods described in Table 12.

4.11.4 Fuel synthesis upgrading

The final step is the fuel synthesis and final product upgrading. The syngas (consisting of H_2 and CO) is catalytically converted via the FT process at high pressures (2000–5000 kPa) and medium temperature (200–350°C), using Co or Fe catalysts (Dell'Aversano et al., 2024). The raw product from the FT synthesis is called syncrude and is a mixture of hydrocarbons. For FT-Diesel a Co-based catalyst is preferred, as it shows better selectivity towards long-chain saturated hydrocarbons, which is especially desired when producing diesel. The product upgrading section consists of separation by condensation, followed hydrocracking of the $>C_5$ and wax fractions, and lastly distillation to separate the different fractions. The aqueous product is treated as wastewater. This process is at TRL 7–8, given that there are several operational demonstration plants (IEA Bioenergy, 2025).

4.11.5 Water abstraction requirements

The water footprint for e-diesel derived from the FT process varies greatly depending on the derivation of the feedstock. Water is required during the reverse water gas shift reaction, in order to reduce CO_2 to CO. Water is also required in cooling systems and heat exchangers for regulating temperature, with approximately 0.62kg of cooling water required for 1kg of fuel (Treyer et al., 2021). Wastewater is also extracted during the process, in the condenser step. This may be treated at an on-site water treatment facility and used as cooling water or to produce ultrapure make-up (boiler-grade) water for the RWGS step.

4.11.6 Pollutants generated through the production of e-Diesel by Fischer-Tropsch

Table 33 summarises the products identified as possible pollutants that are generated during the production of e-Diesel by Fischer-Tropsch. However, production occurs within a closed system during normal plant operation, so the risk of these pollutants being emitted to air or water pathways is minor.

Table 33. Summary of possible pollutants from the e-Diesel via Fischer-Tropsch process

Pathway	Production Step (Source)	Pollutants
Air	Feedstock production	Same as for e-methane via methanation; see section 4.4.4 and Table 17.
	Gas conditioning	CO, CO_2, H_2
	Fuel synthesis and upgrading	CH_4, CO_2, CO, H_2
Water	Feedstock production	Depending on the CO_2 capture process, liquid solvents used in the selected process are considered as pollutants in case of leakage.
	Gas conditioning	Dissolved gases (CO, H_2, CO_2) Excess moisture from the process may be contaminated with metals from the catalysts
	Fuel synthesis and upgrading	Some hydrocarbons and oxygenated by-products (alcohols, aldehydes, ketones, organic acids) might end up in the aqueous phase, along with catalyst dust from the catalytic reactions. Wastewater, potentially contaminated with trace amounts of dissolved gases (CO_2, CO, H_2, CH_4 or other organic phase), and catalyst degradation products.
Land	Unlikely to be any emissions to land.	

4.11.7 Emissions to water

There are two major pathways for impacts to water in the generation of e-Diesel via the FT process. The first is during the gas conditioning stage and the second is during the upgrade of synthesised fuel.

Gas conditioning involves the production of excess water, which may be contaminated with other components of the process such as metals from the catalysts and dissolved gasses. Suitable catalysts include Fe, Mo, Co, Cu, and Ni-based catalysts that support noble metals such as Pt, Pd, Rh, Ru and Au. Catalyst dust from the RWGS process may become entrained in the wastewater following the removal of water during condensation. Similarly, Co and Fe catalysts used for the FT reaction may be present in the wastewater product from hydrocracking.

The primary gases that may be dissolved in the wastewater include CO and CO_2, generated following the RWGS process. Whilst CO reacts with water to produce H_2O and CO_2, when CO_2 dissolves in water it reacts to produce carbonic acid, lowering the pH.

Further wastewater is produced during the synthesis and fuel upgrade stage of the FT process. This wastewater contains hydrocarbons and oxygenated by-products from the refining process. It is generally characterised by a high chemical oxygen demand and low pH and contains a mixture of components including alcohols, aldehydes, ketones and other carboxylic acids (Wang et al., 2017). While these organic components are commonly recycled via rectifying columns, residual alcohols and carboxylic acids remain present within the wastewater. These organic components typically comprise approximately 1% of the total mass in FT wastewater, consisting mostly of alcohols (~0.7%), aldehydes (~0.2%), and ketones (0.1%) (Rahman et al., 2021). Therefore, further treatment is required prior to release to the environment or recycling within the system, typically through the use of water distillation units, as described in Section 4.5.8.

Additional waste streams can be found through the production of the demineralised water that is required for WGS, as described in Section 4.3.8.

4.11.8 Emissions to air

Impacts to air can occur across the feedstock production, gas conditioning, and fuel synthesis and upgrading stages of the production of e-Diesel via the FT process.

The feedstocks to produce e-Diesel via the FT process are H_2 and CO_2, as for e-methane via methanation, covered previously. Therefore, the same risks associated with the production of H_2 and capture of CO_2 apply and can be minimised through best practice in capture and storage. The gas conditioning and fuel synthesis and upgrading are all undertaken within a closed system. Once the fuel has been synthesised there is unlikely to be a direct risk of impact on air.

Techniques for wastewater treatment are discussed in detail in Section 4.13.1.

4.11.9 Emissions to land

The e-Diesel production pathway described here is based on renewable energy, green hydrogen production, and carbon capture technologies. No evidence was found in the literature of risks to land from the operation of this part of the process. If the e-Diesel FT synthesis is integrated with biomass gasification as a feedstock for producing syngas, the process may generate inorganic ash as a by-product, with impacts similar to those discussed in Section 4.3.10.

4.12 Green Ammonia

4.12.1 Process description

Figure 10 presents a process diagram for the production of ammonia from renewable hydrogen via the Haber-Bosch (H-B) process.

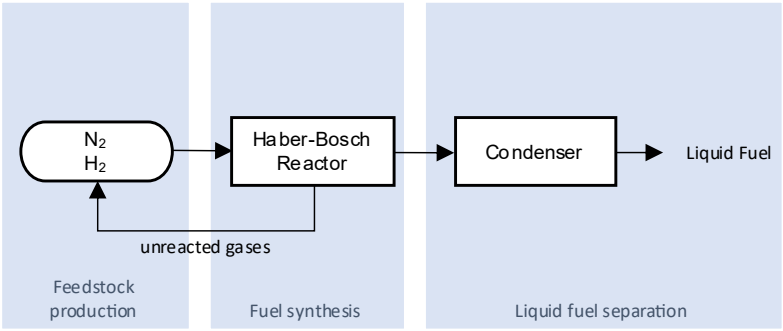

Figure 10. Process diagram for the production of ammonia by the Haber-Bosch process

4.12.2 Feedstock production

The feedstock for ammonia production consists of green hydrogen and nitrogen, with green hydrogen production via electrolysis, and nitrogen obtained from air separation.

Green hydrogen can be produced from the electrolysis of water using renewable energy sources (i.e. wind, solar). If using seawater rather than fresh water, it must be purified by desalination, which can produce brine products; however, direct seawater electrolysis is still in its early stages, with a TRL of 3–4 (Yu et al., 2023). Conventional water electrolysis typically requires around 40–60 kWh/kg_{H2}, while direct seawater electrolysis is 10–20% less efficient (requiring an estimated 55–70 kWh/kg_{H2}) (Franco & Giovannini, 2023). Electrolysis has only recently become commercially viable due to its widespread upscaling.

Depending on the electrolyser system, small amounts of solvent (i.e. NaOH) may enter wastewater streams. Alkaline electrolysers have a higher risk of contaminating water streams with solvent if not operated appropriately, potentially due to diaphragm degradation or system overpressure. Proton Exchange Membrane electrolysers have a much lower risk of contaminating the water stream due to the use of deionised water, so leaks are less harmful unless acidic degradation products are released (Environment Agency, 2024).

Nitrogen can be obtained from air via an air separation unit (ASU). This technology is commercially available and scalable, with a TRL of 9 (Cameli et al., 2024). An ASU compresses air to high pressure and cools it to cryogenic temperatures in order to separate nitrogen from other gases in the air, based on their varying boiling points. Air separation methods may release inert gases; however, these are components of the air

which are simply returning to the air. Argon may be present in the ASU at concentrations up to 10 ppm, with CH_4 and H_2 at concentrations less than 0.1 ppm each. An ASU contains a refrigeration unit to cool the air. Depending on the type of air separation used, the units may use solvents (i.e. hydrochlorofluorocarbons, fluorinated gases, chlorinated solvents), which may leak into the atmosphere if not properly controlled (WG-5 Environment, 2017).

Primary challenges to the advance of e-ammonia synthesis lie in expanding green electricity infrastructure and increasing the manufacturing capacity of electrolyser stacks (Maersk Mc-Kinney Moller Center, 2024).

4.12.3 Fuel synthesis

Following the production of H_2 and N_2, the gases are compressed to a high pressure (15000–30000 kPa) and heated to a temperature of between 400 and 550°C (Seyedehhoma, et al., 2021). They are then reacted in the Haber-Bosch (H-B) reactor under an iron-based catalyst to produce ammonia (International PtX Hub, 2024), a process that is currently widely commercialised.

Due to the large energy requirements of fuel synthesis (compression, heating, reactor operation), producing the energy will also produce CO_2 unless renewable energy sources are used to minimise the CO_2 production. Additionally, the product stream contains unreacted H_2 and N_2, which may leak into the atmosphere. The catalysts used in synthesis (e.g., iron) may introduce metal contaminants into the ammonia product if not properly managed.

E-ammonia production is currently TRL 8 (S&P Global, 2024), with various small-scale e-ammonia plants currently under construction. These include the Baotou Green Hydrogen and Ammonia Demonstration Project (China), Yara Engie Pilbara (Australia), Eyre Peninsula Gateway Project (Australia), Monolith Redwood City Olive Creek 2 (US) and C-Zero Pyrolysis Pilot (US) (IEA, 2024b). A few small-scale plants are currently operational, including Yara Linde Engineering Porsgrunn (Norway), and Fertiberia & Iberdrola in Puertollano (Spain).

4.12.4 Liquid fuel separation

The products from the H-B reactor (ammonia, unreacted feedstock) are sent to the condenser to cool and separate out the liquid ammonia, and the gas mixture (NH_3, H_2, and N_2) is cooled. Under atmospheric pressure, NH_3 condenses into a liquid at approximately -33°C. However, the system's high pressure (15000–30000 kPa) causes liquefaction to occur at higher, more practical temperatures ranging from -10°C to 0°C. The condensed NH_3 is drained as a liquid from the bottom of the separator, while unreacted H_2 and N_2 remain gaseous and are recycled back to the reactor, to undergo further reactions (A World Of Energy, 2023).

4.12.5 Water abstraction requirements

Process water is not required for the process steps of the Haber-Bosch process. The predominant water requirement for the production of ammonia relates to the electrolysis of water to produce green H_2; however, hydrogen production is outside the scope of this study.

Water is required for utility requirements in the process, as is summarised in Table 34. For e-ammonia synthesis, a techno-economic assessment indicates water requirements of 1.62kg for 1kg of liquid ammonia. While literature sources do not provide specific purity requirements for cooling water in ammonia production, they suggest that the requirements are less stringent than for process water (e.g. hydrogen production requires demineralised water), with the main concerns being corrosion prevention and efficient heat transfer.

Table 34. Ammonia water abstraction requirements: Haber Bosch with renewable H_2

Process step	Water abstraction requirement
Fuel synthesis	Water is required in heat exchangers, as steam, to regulate the temperature of the HB reactor (400–500°C).
Liquid fuel separation	Water is required to act as a condenser, to cool the gaseous ammonia to liquid.

4.12.6 Pollutants generated during the production of ammonia by Haber-Bosch

Table 35 summarises potential pollutants generated during the different process steps. However, during normal plant operation, fuel production is within a closed system, so the risk of these pollutants being emitted to air or water pathways is minor.

Table 35. Summary of possible pollutants from ammonia production by Haber-Bosch

Pathway	Production Step (Source)	Pollutants
Air	Feedstock production	Particulate matter and various other pollutants depending on source

Pathway	Production Step (Source)	Pollutants
	Fuel synthesis	CO_2,[22] H_2, N_2, particulate matter,[23] NH_3 (gas)
	Liquid fuel separation	CO_2, NH_3 (gas)
Water	Feedstock production	Electrolysis solvent (i.e. NaOH, KOH)
	Fuel synthesis	Excess moisture from the process may be contaminated with metals from the catalysts
	Liquid fuel separation (condenser)	-
Land	Unlikely to be emissions to land.	

4.12.7 Emissions to water

The predominant water impact risks relating to the production of ammonia are attributed to the production, storage and transport of the ammonia itself. While ammonia is an essential nutrient involved in the nitrogen cycle, when converted to nitrate (NO_3^-) by bacteria, excess ammonia can pose significant risks to freshwater ecosystems due to its toxicity to aquatic life and propensity to cause eutrophication (Smith, 2003; Camargo & Alonso, 2006).

Ammonia is highly soluble in water and has the potential to enter aquatic environments through wastewater discharges (if untreated), such as the coolant wastewater produced during fuel separation, or through leaking vessels and pipes. Excess moisture produced during fuel synthesis can contain large concentrations of ammonia (up to 1kg/m^3), as well as other metal contaminants such as iron, used as catalysts during the Haber-Bosch reaction (Fertilizers Europe, 2000). This wastewater can be re-used as boiler feedwater following ion-exchange treatment. Ammonia can also be recovered from wastewater through ammonia air-stripping and absorption (Haiyuan et al., 2018).

Generally, if storage vessels are designed, operated and maintained well, emissions of ammonia during storage will be negligible. Most leaks occur during the transport and transfer of ammonia. However, releases are mitigated and/or reduced during transport through best available techniques for ammonia production, including isolation valves in

[22] Indirect, from energy source (i.e. from fuels used to produce heat for the process).

[23] Formed when ammonia mixes with other gases in the atmosphere.

transfer pipelines and the use of scrubbers/absorbers to prevent emissions to the atmosphere (Fertilizers Europe, 2000).

Section 4.13.1 provides a more detailed description of wastewater treatment techniques.

4.12.8 Emissions to air

Ammonia poses minimal direct air impact risks, as it dissipates after a few hours once emitted to the atmosphere. However, when ammonia mixes with other gases such as nitrogen oxides and sulphur dioxide, it forms ammonium salts, which are a major component of PM. PM can exist in the atmosphere for several days and be transported large distances. There are significant health concerns associated with exposure to PM concentrations (DEFRA, 2024). Unreacted N_2 and H_2 are contained in the product stream of the Haber-Bosch process and are typically recycled to improve process efficiency, as outlined in Section 4.12.1 above. Unreacted nitrogen does not pose a risk, but hydrogen, while not directly acting as a greenhouse gas, can prolong the atmospheric lifetime of methane by interfering with its breakdown process (Department for Business, Energy & Industrial Strategy, 2022).

Fugitive emissions may occur during ammonia production, transportation, storage and combustion. These emissions include reactive nitrogen compounds (e.g. NH_3, NO_x, N_2O) and are estimated to range between 0.5% and 5% of total nitrogen fixed into ammonia. However, there is significant uncertainty in the levels of reactive nitrogen that may be released, due to the relative immaturity of the supply chain (Bertagni et al., 2023).

4.12.9 Emissions to land

Globally, leakages across the ammonia value chain and undesired reactions during ammonia use lead to the release of reactive nitrogen compounds (e.g., NH_3, NO_x, N_2O, HONO (or nitrous acid)) into the environment. A 5% loss rate of nitrogen for ammonia production could be enough to perturb the global nitrogen cycle (Bertagni et al., 2023) by an amount equivalent to 50% of the current global perturbation caused by fertilisers. The estimated 5% loss rate by these authors (loss of nitrogen drawn from the atmosphere for ammonia production that is lost to the environment) is the upper bound of a range (0.5 to 5%).

Ammonia vapours are likely to dissipate, reacting with moisture in the air to form ammonium. Ammonium will bind to soil organic matter and soil clays (Nieder et al., 2011) (due to the negative charged particles), and it rarely accumulates in soil because bacteria convert it to nitrates (nitrification) (Hernández-Guzmán et al., 2022). However, from an environmental perspective, ammonia leakage into soil can cause biodiversity loss (Nemmour et al., 2023). Diffuse ammonia pollution has the potential to damage a wide environment, particularly at sensitive (low nutrient) sites or sites where nutrient levels are already close to critical damage thresholds. Examples of such ecosystems include heathland, grassland and some peatlands, where changes in nitrogen levels within the soil could change the entire plant community and ecosystem. Reactive nitrogen impacts

vegetation biodiversity through direct foliar damage, eutrophication, acidification, and susceptibility to secondary stress (Dise et al., 2011). Gaseous ammonia has been found to be particularly harmful to vegetation, while ammonia vapours are toxic to livestock (Nemmour et al., 2023). However, ammonia has low levels of persistence on land (due to conversion and release as N_2O/NO_x and high solubility, leading to leaching into ground water and watercourses), which may pose a bigger risk to biodiversity in the long term. If the pH of the soil is low (acidic), the impact of ammonia increases, as this reduces its conversion to ammonium. Conversely, as ammonium it would remain bound to soil particles for longer, leading to changes in nitrogen levels within the soil profile, for example in peatland habitats.

4.13 Further Considerations

4.13.1 Wastewater management solutions

Wastewater effluent treatment is a necessary ancillary system to support the operation of chemical plants and ensure regulatory permits are being met (National Energy Technology Laboratory, 2022). Treatment can be employed at “end-of-pipe” prior to discharge into receiving water bodies, reducing the potential for environmental impact from aqueous emissions. This can be conducted at source, treating effluent at decentralised wastewater treatment facilities, or combined with other effluent at centralised wastewater treatment facilities (Joint Research Centre: Institute for Prospective Technological Studies, 2016). Wastewater can also be discharged to municipal wastewater treatment plants; however, pre-treatment may be required at source. The most appropriate treatment processes depend on the composition and concentration of pollutants present within the wastewater effluent, and potential synergistic or antagonistic effects between pollutants. For example, some pollutants, such as heavy metals or non-biodegradable compounds, can escape treatment if diluted during combination with other effluent streams due to their persistent nature. Some treatment processes are effective at treating numerous pollutants simultaneously, such as aerobic or anaerobic digestion, which can degrade a wide range of biodegradable matter. Other pollutants can disrupt biological treatment processes and thus should be removed beforehand (Sravan et al., 2024).

Table 36 summarises some of the best available techniques for end-of-pipe wastewater treatment for pollutants identified within this study. A more encompassing list can be found in the Best Available Technology reference document produced for the European Commission on common wastewater and waste gas treatment in the chemical sector (Joint Research Centre: Institute for Prospective Technological Studies, 2016).

Table 36. List of wastewater treatment techniques for pollutants identified within this study

Technique	Treatment Overview	Pollutants
Coagulation/ Flocculation	Destabilises particles’ surface charges (coagulation), allowing particles to clump together into larger particles. Larger flocs form through mixing.	Heavy metals, sulphides, hydrocarbons (undissolved), suspended solids, organic compounds
Adsorption	Transfer of soluble substances from the aqueous phase to the surface of a highly porous solid.	Halogenated compounds, ammonia, heavy metals, hydrocarbons, nitro compounds

Technique	Treatment Overview	Pollutants
Nanofiltration/ Reverse Osmosis	Filtration and separation of particles through a membrane, based on their particle size and ionic charge.	Ammonia, phosphates, heavy metals
Neutralisation	Adjustment of pH to neutral (pH 7) through addition of acidic or alkaline chemicals.	Acids, Alkalis
Flotation	Attachment of particulates to gas bubbles that are accumulated and collected at the water surface.	Heavy metals, hydrocarbons
Biological Treatment	Breakdown of organic matter via aerobic or anaerobic bacteria.	Alcohols, aldehydes, ammonia, ketones, biodegradable halogenated compounds, heavy metals, sulphates, phenols

Many of the fuels discussed in this study can produce organic byproducts such as alcohols, aldehydes, ketones, and hydrocarbons that are also classified as volatile organic compounds, characterised by their ability to easily evaporate into the air. Any VOCs present in wastewater effluent can be emitted to air if exposed to the atmosphere during wastewater treatment processes (Lim et al., 2023). Thus, further waste gas treatment techniques may also be required, in combination with wastewater treatment techniques, to mitigate emissions to air. Such techniques include wet gas scrubbers, oxidation techniques and biofiltration (Joint Research Centre: Institute for Prospective Technological Studies, 2016).

4.13.2 Challenges in the comparison of water consumption across production pathways

This study has included scientific literature highlighting the water consumption of the various production pathways. However, comparisons between the water consumptions of individual fuels should be treated with caution due to the inherent differences between studies. Variations in operational parameters across studies can significantly affect reported water consumption values. Differences in operational values for parameters surrounding crop cultivation, water usage in production processes, energy consumption, and product yield will result in discrepancies between studies, resulting in a lack of standardisation and hindering meaningful comparison. In addition, many of the fuel technologies studied lack extensive water footprint analyses, due to their lower technology readiness. Without comprehensive life cycle assessments for these fuels, water consumption data for some individual production steps remains unavailable.

If a more accurate assessment of water consumption across different fuel technologies is required, additional research and a standardisation of methodologies will be needed.

5 Existing Regulatory Measures

This section presents an overview of the existing regulatory measures that may be applicable to the alternative fuels in the scope of this study and identifies potential gaps in the regulatory framework.

The regulatory measures considered include those related to the production, transport and storage of the alternative fuels. While the analysis was comprehensive, the list may not be exhaustive. It should also be noted that this analysis reflects the scope of legislation at the time of the analysis (October 2024 to January 2025).

This analysis is summarised in Table 37 and details are provided in the appendix.

Table 37. Summary of the applicability of existing UK Regulations to the alternative fuels considered in this report

Regulation	Lifecycle Scope	Ammonia	e-/biomethane	Synthetic diesel	SAF
UK REACH	Production	✓	✓	✓	✓
Industrial Emissions Directive 2010	Production	✓	✓	✓	✓
Environmental Permitting Regulations 2016	Production, storage	✓	✓	✓	✓
GHG Emissions Trading Scheme 2020	Production	✓	✓	✓	✓
Health and Safety at Work Act 1974	Production, storage, transport	✓	✓	✓	✓
The Control of Major Accident Hazards Regulations 2015	Any point in the lifecycle where threshold quantities are exceeded (excluding transport)	✓	✓	✓	✓
Control of Pollution (Oil Storage) (England) Regulations 2001	Storage	×	×	✓	✓
The Petroleum (Consolidation) Regulations 2014	Storage	×	×	×	×

Regulation	Lifecycle Scope	Ammonia	e-/biomethane	Synthetic diesel	SAF
The Alternative Fuel Labelling and Greenhouse Gas Emissions (Miscellaneous Amendments) Regulations 2019	Storage	×	✓	✓	✓
The Alternative Fuels Infrastructure Regulations 2017	Other	×	×	×	×
The Carriage of Dangerous Goods and Use of Transportable Pressure Equipment Regulations 2009	Other	✓	✓	✓	✓

6 Risk to Human Health

This section discusses potential public health risks that could arise from emissions of substances to the environment during the production of these fuels. The assessment does not consider workplace exposure, as this is covered within Control of Substances Hazardous to Health Regulations, which require employers to adequately control workplace exposure to hazardous substances and which is regulated by the Health and Safety Executive (HSE). The Environment Agency does not regulate for occupational risk. This section covers the potential human health risk from the most commonly identified pollutants from the alternative fuels production processes described in Section 4 (i.e. those identified in the majority of the processes). These pollutants are not necessarily the most hazardous.

There are four steps in the assessment and management of chemicals to protect public health: hazard identification, hazard characterisation, exposure assessment, and risk characterisation. The first step involves identifying the potential hazards that could arise, i.e. the potential adverse health effects of exposure *via* the different exposure routes (oral, inhalation, and dermal). If sufficient toxicological information is available, these hazards are then characterised to identify the levels of exposure associated with a minimal or non-appreciable risk to public health. Following the characterisation of the hazards, the likelihood and magnitude of exposure and the risk (i.e. the likelihood of the hazard causing harm; EFSA, 2016) are then assessed. Often, this risk assessment involves comparing predicted exposures or media concentrations in air or water (as proxies for exposure) with suitable guidelines or limits protective of public health such as environmental assessment levels (EALs) for air or environmental quality standards (EQS) for water (GOV.UK, 2025a).

To assess the potential risks to public health from environmental exposure, guidelines such as EALs and standards such as some EQS can be used. These are often derived from health-based guidance values (HBGVs), which define exposure levels at which adverse effects are minimal or not appreciable (Environment Agency, 2022b). HBGVs for human health include Tolerable Daily Intakes, which estimate the amount of a substance that can be ingested or inhaled daily over a lifetime without an appreciable, or with a minimal risk to health, expressed on a bodyweight basis (Environment Agency, 2009). For assessment of risks from inhaled substances, a Tolerable Concentration in Air or a Reference Concentration may also be used, which is the mean concentration of a substance in ambient air that can be inhaled over a specified exposure duration (typically an hour, a day, or daily over a year) with a minimal or not appreciable risk to human health (Environment Agency, 2025a). EALs are non-statutory guidelines, which are often based on a Tolerable Concentration in Air or similar HBGV, but they can also be derived from a Tolerable Daily Intake based on ingestion through route-to-route extrapolation. EQSs are limit values which are used for the protection of human health and the environment.

This assessment is a **hazard-based assessment**, as there is insufficient information on, for example, the emission concentrations of the substances and any Risk Management Measures (RMMs) that could be put in place to reduce emissions of these substances, to

derive conclusions on the **risks**. There **is insufficient information on emissions**, as many of these plants are not yet in operation. However, as plants approach operational status, an estimate of emissions levels will be required for regulatory purposes. For example, one study is available for an e-fuels plant (production of e-kerosene and e-diesel) in Denmark, where air emissions were calculated for nitrogen dioxide (35 µg/m^3), sulphur dioxide (64 µg/m^3), and carbon monoxide (84 µg/m^3) during normal operations. This includes emissions from operation of the safety torch, steam destruction plants and the CO_2 purification column (Danish Environmental Protection Agency, 2025).

The following sections identify the human health hazards from the most common pollutants that can be emitted and provide potential guidelines for hazard characterisation (where available). A pollutant-based approach has been used rather than a process-based approach, as many of the pollutants can be emitted from multiple processes.

For the potential adverse human health effects resulting from exposure (unless otherwise stated), the European Chemicals Agency (ECHA) Classification and Labelling Inventory has been used to identify the human health hazards (ECHA, 2025). The Control of Major Accident Hazards Regulations 2015 (COMAH) would be applicable for a number of these processes (see Section 4). Where available, information is provided on EALs and/or EQSs for these pollutants; otherwise, DNELs are given.

6.1 Key pollutants

6.1.1 Hydrogen

Hydrogen is a pollutant which could potentially be released in all ten of the alternative fuel processes (Table 38), with air being the relevant exposure media. Hydrogen is classified for physical hazards only (H220; Flam. Gas 1 (Flammable Gas Category 1); Press. Gas (Pressurised Gas)). Hydrogen can displace oxygen and cause rapid suffocation (Airgas, 2025). There are no EALs, EQSs or DNELs for hydrogen.

Table 38. Production processes in which hydrogen may be emitted

Production	Step	Additional considerations
Biomethane production via gasification and methanation	• Gasification (air) • Gas cleaning and conditioning (air) • Fuel synthesis and upgrading (air)	Hydrogen can be present as a component of the product gas during gasification and gas cleaning and conditioning. Hydrogen is used as a gas stream for fuel synthesis and upgrading.

Production	Step	Additional considerations
E-methane via methanation	• Fuel synthesis and upgrading (air, water)	Hydrogen is one of the inputs for the process.
FT-SPK	• Gasification (air) • Gas cleaning and conditioning (air) • Fuel synthesis and upgrading (air)	Hydrogen can be present as a component of the product gas during gasification and gas cleaning and conditioning. Hydrogen is an input for fuel synthesis and upgrading.
FT-SKA	• Aromatisation (air) • Hydrotreating (air)	Present as a component of syngas (input).
AtJ-SPK and AtJ-SKA	• Hydrogenation (air)	Input for hydrogenation.
SAF/diesel via pyrolysis	• Pyrolysis (air) • Products separation (air)	Used as a gas stream.
SAF or diesel via hydrothermal liquefaction	• Feedback conversion (air)	
e-Diesel via Fischer-Tropsch	• Gas conditioning (air, water) • Fuel synthesis and upgrading (air, water)	Can be present as dissolved gas in wastewater from fuel synthesis and upgrading.
Green Ammonia by Haber-Bosch	• Fuel synthesis (air)	Unreacted hydrogen is contained in the product stream and could leak to air.

6.1.2 Methane

Methane is a potential pollutant that could be released to air in nine of the alternative fuel processes (Table 39). The processes that could release methane to air are: biomethane production by gasification; e-methane production by methanation; synthetic paraffinic kerosene via gasification and FT; AtJ-SPK; AtJ-SKA; SAF/diesel via pyrolysis; e-Diesel via FT; and SAF/diesel via hypothermal liquefaction. There could also be potential release to water in FT-SPK and FT-SKA, AtJ-SPK and AtJ-SKA and e-Diesel via Fischer-Tropsch.

Methane, like hydrogen, is classified for physical hazards only. However, methane can cause rapid suffocation, and avoiding breathing the gas is also advised (ECHA, n.d.(a); CK Special Gases Ltd, n.d.). Methane can reduce the oxygen concentration in air, leading to potential health effects such as nausea, vomiting, slurred speech, visual problems, headache, changes in mood and memory loss (GOV.UK, 2024a).

Table 39. Production processes in which methane may be emitted

Production	Step	Additional considerations
Biomethane via gasification and methanation	• Gasification (air) • Gas cleaning and conditioning (air) • Fuel synthesis and upgrading (air)	Component of the product gas.
E-methane via methanation	• Feedstock production (air) • Fuel synthesis and upgrading (air)	Methane can be present in the CO_2 stream from feedstock production. There is the possibility of methane leakage during compression or storage.
FT-SPK and FT-SKA	• Fuel synthesis and upgrading (air) • Gas cleaning and conditioning (water)	Process is performed in closed systems. Potential of release during venting, purging or maintenance. Potential leakages through pressure relief valves and gas cleaning operations.
AtJ-SPK and AtJ-SKA	• Hydrogenation (water)	Gaseous hydrocarbons such as methane may be present in the aqueous phase from hydrogenation.
SAF or diesel production via pyrolysis	• Pyrolysis (air) • Products separation (air, water)	Process is undertaken in closed systems.
SAF or diesel via hydrothermal liquefaction	• Feedstock conversion (air)	Similar to FT-SPK (described above).
e-Diesel via Fischer-Tropsch	• Feedstock production (air)	Production is undertaken in closed systems. Methane may be present in the stream produced during feedstock production.

Production	Step	Additional considerations
	• Fuel synthesis and upgrading (air and water)	

6.1.3 Ammonia

The potential for ammonia emission has been identified in nine of the production processes (Table 40), with air as the main exposure media. The potential risk to human health from ammonia depends on the RMMs used during the production process; however, closed systems are generally used as described in Section 4. Water is also a potential exposure media for three of the production processes: biomethane production by gasification, AtJ-SPK and AtJ-SKA, and SAF or diesel via hydrothermal liquefaction.

Ammonia can be toxic if inhaled. Inhalation exposure to low levels of ammonia can also cause eye, throat and noise irritation, while inhalation exposure to high levels of ammonia can result in damage to airways (burns and swelling) and lungs (GOV.UK, 2024b). Ammonia is also an important precursor for PM2.5 formation, as it bonds with other atmospheric gases (Gu et al., 2021). The health effects for PM2.5 are discussed in Section 6.1.5. Ammonia has a one-hour mean limit value of 2500µg/m^3 and an annual mean value of 180µg/m^3 as EALs.

Where water is the exposure media, oral exposure to ammonia solutions can result in aerodigestive tract burns, pain and excessive salivation. If there is substantial oral exposure, this can result in burns to the oral cavity, larynx, nasopharynx and trachea. Airway obstruction, alveolar and bronchiolar oedema and respiratory distress can also result from substantial oral exposure (GOV.UK, 2024c). Under the UK drinking water quality regulations, there is a guidance value of 0.5mg/L for ammonia (DWI, 2015).

Table 40. Production processes in which ammonia which is hazardous to human health may be emitted

Production	Step	Additional considerations
Biomethane production by gasification	• Gasification (air) • Gas cleaning and conditioning (air and water)	Ammonia can be removed via wet scrubbing to reduce emissions to water. Ammonia is removed (as an impurity) during gas cleaning and conditioning.
Synthetic paraffinic kerosene via gasification and FT	• Gasification (air) • Gas cleaning and conditioning (air)	

Production	Step	Additional considerations
FT-SKA and FT-SPK	• Hydrotreating (air)	Ammonia is a potential pathway if nitrogen impurities are present in the feedstock.
AtJ-SPK and AtJ-SKA	• Fractionation (water)	Can be present in the wastewater generated in the atmospheric distillation units.
SAF/diesel via pyrolysis	• Pyrolysis (air)	Ammonia can be removed via wet scrubbing to reduce emissions to water. Composition of pollutants can be dependent on the feedstock (as per FT-SKA and FT-SPK).
SAF or diesel via hydrothermal liquefaction	• Feedback conversion (air) • Fuel upgrading (water)	As above, and fugitive emissions of ammonia can also occur to air. Ammonia can be removed via wet scrubbing to reduce emissions to water.
Green Ammonia by Haber-Bosch	• Fuel synthesis (air) • Liquid fuel separation (air)	Fugitive emissions of ammonia can occur during production.

6.1.4 Carbon oxides

6.1.4.1 Carbon monoxide

The potential emission of carbon monoxide (CO) to the air (inhalation exposure) has been identified in eight of the alternative fuel production processes, summarised in Table 41. Additionally, CO can be present as dissolved gases during gas conditioning for several of the processes with water as the exposure media. However, oral exposure is not considered as a route of exposure for CO (ATSDR, 2012). The potential risk to human health from CO will depend on the RMMs used during the production process. However, closed systems are generally used, as described in Section 5.

Following inhalation exposure, CO is toxic from repeated exposure and can result in a number of symptoms including dizziness, headaches and vomiting (CO Research Trust, 2025), with air as the key exposure media. CO has a limit value of 10 mg/m^3 (8-hour

mean) in air under the Air Quality Standards 2010. There is also a 1-hour mean EAL of 30,000 µg/m^3.

Table 41. Production processes in which CO which is hazardous to human health may be emitted

Production	Step	Additional considerations
Biomethane production via gasification and methanation	• Gasification (air) • Gas cleaning and conditioning (air) • Fuel synthesis and upgrading (air)	Fugitive emissions of CO can occur during the storage of biomass and bio-waste feedstocks. CO is also a component of syngas.
E-methane production by methanation	• Feedstock production (air) • Fuel synthesis and upgrading (air, water)	Maintenance and emergency shutdowns could lead to emission of CO. CO can be present as an additional gaseous component in the gas stream during feedstock production.
FT-SPK and FT-SKA	• Gasification (air) • Gas cleaning and conditioning (air, water) • Fuel synthesis and upgrading (air)	Fugitive emissions of CO can occur during the storage of biomass and bio-waste feedstocks. CO is used as a feedstock for this process and is a component of the syngas.
AtJ-SPK and AtJ-SKA	• Dehydration and separation (air) • Fractionation (air)	Incomplete combustion can result in CO being emitted to air.
SAF/diesel via pyrolysis	• Pyrolysis (air) • Products separation (air, water)	In pyrolysis, the composition of the mixture produced (and the CO concentration) depends on the feedstock and gasifying agent (Mariyam et al., 2022). For water, the potential concentrations can depend on the process conditions and feedstock.

Production	Step	Additional considerations
e-Diesel via FT	• Feedstock production (air) • Gas conditioning (air, water) • Fuel synthesis and upgrading (air, water)	In feedstock production, the composition of emissions can depend on the CO_2 source. CO can be present in the resulting stream in feedstock production. Gas conditioning and fuel synthesis and upgrading are performed in closed systems.

6.1.4.2 Carbon dioxide

The potential emission of carbon dioxide to the air (inhalation exposure) has been identified in nine of the alternative fuel production processes. The emissions of carbon dioxide are the same as those for carbon monoxide (Table 41), with the additional production process being SAF/diesel via hydrothermal liquefaction: Feedstock conversion (air).

UK Health Security Agency (UKHSA) guidance states that exposure to low levels of carbon dioxide (which is also a physical hazard) would not be expected to result in human health effects. However, exposure to high levels in enclosed spaces can lead to asphyxiation if the oxygen concentration in air is reduced (GOV.UK, 2024d). This guidance does not define “low” and “high” levels of exposure.

6.1.5 Particulate Matter

The potential emission of particulate matter has been identified in seven of the production processes, with air as the exposure media. These are summarised in Table 42. The potential risk to human health from PM depends on the RMMs used during the production process; however, closed systems are generally used, as described in Section 4.

Exposure to particulate matter (via inhalation exposure) contributes to both lung cancer and heart disease (GOV.UK, 2018). Limit values are in place for particulate matter under the Air Quality Standards 2010 (GOV.UK, 2025b). These are 20 $\mu g/m^3$ (annual mean) for $PM_{2.5}$ and 40$\mu g/m^3$ (annual) and 50$\mu g/m^3$ (24 hours, not to be exceeded more than 35 times annually) for PM_{10}. There are no EQS limits for PM.

Table 42. Production processes in which PM2.5/PM10 which is hazardous to human health may be emitted

Production	Step	Additional considerations
Biomethane production via gasification and methanation	• Feedstock storage and pre-treatment (air) • Gasification (air) • Gas cleaning and conditioning (air and water)	During feedstock storage and pre-treatment, the emission of PM depends on the feedstock used and the pre-treatment process. PM can become entrained in the product gas during feedstock conversion. It is then removed as an impurity during gas cleaning and conditioning (potential emission).
E-methane via methanation	• Feedstock production (air)	Emissions can depend on the CO_2 source and the capture method. PM can be present in the stream produced during feedstock production.
Synthetic paraffinic kerosene via gasification and FT	• Feedstock storage and pre-treatment (air) • Gasification (air) • Gas cleaning and conditioning (air)	During feedstock storage and pre-treatment, the emission of PM depends on the feedstock used and the pre-treatment process. PM is removed as an impurity during gas cleaning and conditioning.
AtJ-SPK and AtJ-SKA	• Dehydration and separation (air) • Fractionation (air)	The level of PM emitted depends on whether incomplete combustion occurs.
SAF/diesel via pyrolysis	• Feedstock storage and pre-treatment (air) • Pyrolysis (air) • Products separation (air)	The level of PM emitted depends on the feedstock and the pyrolysis technology used. PM is removed as an impurity during products separation.
Green Ammonia	• Feedstock production (air) • Fuel synthesis (air)	PM emissions also depend on the feedstock source.

Production	Step	Additional considerations
		PM is formed during fuel synthesis when ammonia mixes with other gases in the atmosphere.

6.1.6 Hydrogen sulphide

The potential emission of hydrogen sulphide has been identified in seven of the production processes. Air is an exposure media for all seven production processes, while water is a potential exposure media in three. These are summarised in Table 43. The potential risk to human health from hydrogen sulphide depends on the RMMs used during the production process; however, closed systems are generally used, as described in Section 4.

Hydrogen sulphide is classified under the Classification, Labelling and Packaging Regulations as being toxic by inhalation. Inhalation is the primary route of exposure. Inhalation exposure to low concentrations can result in eye and respiratory tract irritation, with symptoms including sore throat, cough and dyspnoea. Irritant effects have been reported at concentrations above approximately 28 mg/m^3 (20 ppm), although effects cannot be ruled out at lower concentrations. Exposure to high concentrations may result in rapid collapse, respiratory paralysis, convulsions, coma and death within minutes, and concentrations around 700 mg/m³ (500 ppm) or above may be fatal (GOV.UK, 2025c). Hydrogen sulphide has a 24-hour mean limit value of 150 µg/m^3 (short term) and an annual mean limit value of 140 µg/m^3 as EALs. For oral exposure, no hazards have been identified (ECHA, n.d.(b)), so there are no EQS values for hydrogen sulphide in water.

Table 43. Production processes in which hydrogen sulphide which is hazardous to human health may be emitted

Production	Step	Additional considerations
Biomethane production by gasification	• Gasification (air) • Gas cleaning and conditioning (air, water)	Potential for unintentional emissions. Emissions could occur during maintenance and during venting/purging. Hydrogen sulphide is emitted during gas cleaning and conditioning. It can also be present as an impurity in syngas.
E-methane production by methanation	• Feedstock production (air)	Potential emissions from leakage. Hydrogen sulphide may be present in the CO_2 stream but is removed.

Production	Step	Additional considerations
Synthetic paraffinic kerosene via gasification and FT	• Gasification (air) • Gas cleaning and conditioning (air, water)	Potential for unintentional emissions during maintenance or venting/purging. Hydrogen sulphide is emitted during gas cleaning and conditioning. It can also be present as an impurity in syngas.
FT-SKA and FT-SPK	• Hydrotreating (air)	Potential emissions from leakage, venting and purging. Removed as an impurity during hydrotreating.
SAF/diesel via pyrolysis	• Pyrolysis (air) • Products separation (air, water) • Fuel upgrading (air)	Levels emitted depend on the feedstock and pyrolysis technology used. This can be released during product separation (hydrodeoxygenation).
e-Diesel via FT	• Feedstock production (air)	Emissions depend on the CO_2 source and capture method. Hydrogen sulphide also needs to be removed prior to CO_2 capture.

6.1.7 Nitrogen oxides

The potential emission of nitrogen oxides[24] (NOx) has been identified in six of the production processes, with air as the exposure media. These are described in Table 44. The potential risk to human health from nitrogen oxide emissions depends on the RMMs used during the production process; however, closed systems are generally used, as described in Section 4.

Nitrogen oxides can be fatal if inhaled, and short-term exposure can cause inflammation of the airways and can also increase susceptibility to allergens and respiratory infections. In addition, nitrogen oxides can react with other air pollutants to produce ozone, which has human health effects (GOV.UK, 2024e). Exposure to ozone can result in coughing, sore throat, and airway damage (US Environmental Protection Agency, 2025). Under the Air Quality Standards 2010, the 1-hour mean limit value for nitrogen dioxide (up to 18 1-hour periods) is 200 µg/m^3, with 40 µg/m^3 as an annual mean. Nitrogen monoxide has a 1-hour mean EAL of 4,400 µg/m^3 and an annual mean EAL of 310 m^3 (GOV.UK, 2025b).

[24] This includes nitrogen monoxide (NO) and nitrogen dioxide (NO_2).

Table 44. Production processes in which NOx which is hazardous to human health may be emitted

Production	Step	Additional considerations
Biomethane production via gasification and methanation	• Gasification (air) • Gas cleaning and conditioning (air)	Potential for unintentional emissions during maintenance or venting/purging. Nitrogen compounds are removed as impurities during gas cleaning and conditioning.
E-methane production by methanation	• Feedstock production (air)	Potential for unintentional emissions. Emissions could occur during maintenance or venting/purging. NOx may be present in the CO_2 stream but is then removed.
Synthetic paraffinic kerosene via gasification and FT	• Gasification (air) • Gas cleaning and conditioning (air)	Potential emissions from incomplete combustion. Nitrogen compounds are removed as impurities during gas cleaning and conditioning.
AtJ-SPK and AtJ-SKA	• Dehydration and separation (air) • Fractionation (air)	The process configuration used can affect the emissions.
e-Diesel via FT	• Feedstock production (air)	Emissions can depend on the CO_2 source and capture method. NO_x also needs to be removed prior to CO_2 capture.

6.1.8 Emissions to land

As described in Section 4, there are unlikely to be emissions to land during the processes. Potential human health impacts from the generated waste streams are discussed in the following sections.

6.1.9 Waste

As described in Section 4, waste streams are generated during the production of these fuels, with consequent emissions to land. These waste streams could contain substances which are hazardous to human health and are further described below for solid and liquid waste for the most common identified pollutants with risks to human health.

6.1.9.1 Solid waste

The most commonly reported pollutants in solid waste in the alternative fuels production processes are ash and char.

Ash is potentially present in the solid waste streams of the following production processes:

- Biomethane via gasification and methanation
- Synthetic paraffinic kerosene via gasification and Fischer-Tropsch
- FT-SKA
- Sustainable aviation fuel or diesel via pyrolysis
- e-Diesel via Fischer-Tropsch

Ash is a source of PM (DEFRA, n.d), and inhalation exposure of PM is discussed in Section 6.1.5. There is limited information for the potential health effects following oral exposure to PM (such as through emissions to land), though neurodevelopmental disorders are reported in the literature (Ruiz-Sobremazas et al., 2025). There is currently no EQS for PM. Ash can also contain high amounts of metals such as calcium and potassium, as described further in Section 4.3.10. Ash in solid waste is typically alkaline (Olea et al., 2024). Calcium is classified for physical hazards only (H261; water-react. 2) (ECHA, n.d.(c)). Potassium is classified for human health as causing eye damage and severe skin burns (Skin Corr. 1B; H314) (ECHA, n.d.(c)). There is no EQS for potassium.

Char may be present in the solid waste streams of the following production processes:

- Synthetic paraffinic kerosene via gasification and Fischer-Tropsch
- FT-SKA
- Sustainable aviation fuel or diesel via pyrolysis
- Sustainable aviation fuel or diesel via hydothermal liquefaction

Inhalation exposure to char can have negative effects on human health; for example, respiratory diseases have been reported for biochar exposure (Pinelli et al., 2024). There are no EQSs for chars (individually or as a group). As described in Section 4.5.10, char can contain small quantities of siliceous ash, which consists of silicon dioxide, alumina and iron oxide (Makul, 2025). Oral exposure to silicon dioxide has been assessed by EFSA (for use as a food additive) as showing no indication of toxicity at the reported levels (EFSA Panel on Food Additives and Nutrient Sources added to Food, 2018). However, inhalation exposure to respirable crystalline silica can lead to silicosis and chronic obstructive pulmonary disease (HSE, n.d.(a)). Aluminium oxide can irritate the skin and eyes, as well as the nose, throat and lungs from inhalation exposure (New Jersey Department of Health, 2017). Iron oxide is not classified as a hazardous substance (Merck, 2025). Char can also contain PAHs. Exposure to PAHs can irritate eyes and breathing passages, with some PAHs also being considered as carcinogens (Centers for Disease Control and Prevention, 2009).

6.1.9.2 Liquid waste

As described in Section 4.13.1, various organic byproducts are produced that could be present in wastewater. These organic by-products are classified as volatile organic compounds (VOCs). Oral exposure to VOCs can result in a variety of health effects such as effects on the cardiovascular, immune, reproductive, immune and respiratory systems (Rodriguez et al., 2012). Some VOCs, such as benzene, are also carcinogenic. There is no EQS for VOCs as a group; however, some individual VOCs have EQSs such as 10 µg/L (annual average) for benzene for freshwater.

6.1.10 Novel pollutants

Other pollutants with potential human health effects can also be emitted during the alternative fuel production pathways. However, information on these can be limited, as was discussed in Section 4. For example, for some pollutants only a general description of the composition is available, not the specific composition (such as light alkanes, unreacted olefins, HCs and phenolic compounds).

Some potential novel pollutants relative to conventional fuel production pathways have been identified. These include:

- Lignin: This could be emitted to water during feedstock production for the AtJ-SPK production pathway. However, lignin is not classified as hazardous to human health (Sigma-Aldrich, 2024).
- Ethanol: This could be emitted to water during dehydration and separation in the AtJ-SPK process. Oral exposure to ethanol can lead to mood changes, slurred speech, nausea and uncoordinated movements (GOV.UK, 2024f). There are no EALs/EQSs for ethanol.

6.2 Comparison of fuels

These alternative fuels have also been compared with conventional fuels to identify any new pollutants and their potential hazards to human health in the fuel products (where such information is available). These have been grouped as follows:

- Biomethane and e-Methane
- Sustainable aviation fuel (FT-SPK, SKA, AtJ-SPK, and AtJ-SKA)
- Synthetic diesel (FT-diesel and e-diesel)
- Ammonia

6.2.1 Biomethane and e-methane

There are not expected to be differences in the composition of biomethane and e-methane, as further discussed in Section 7. The risk to human health from methane is described in Section 6.1.2.

6.2.2 Sustainable aviation fuel

As is discussed further in Section 7.3, sustainable aviation fuel and its conventional equivalent fuel comprises aromatics, cycloalkanes, iso-alkanes and n-alkanes. Conventional aviation fuel, such as the Jet A-1 standard, has the following human health hazards: skin irritation (Skin Irrit. 1; H315); aspiration toxicity (Asp. Tox 1; H304) and single organ toxicity following single exposure (STOT SE 3; H336) (BP, 2014).

For SAFs, as discussed in Section 7.3, it is expected that there may be differences in the aromatic composition of these fuels. In the case of synthetic paraffinic kerosene with aromatics (AtJ-SKA), benzene, toluene and xylene are added to the fuels.

Benzene is a carcinogenic substance for human health (IARC, 2018). Under the Air Quality Standards 2010, benzene has limit values of 5 µg/m^3 (annual mean) and 30 µg/m^3 (24-hour mean) in air. Benzene also has an EQS of 10 µg/m^3 as an annual average in freshwater, with a maximum allowable concentration of 50 µg/m^3. Health effects of toluene following inhalation, oral and/or dermal exposure include dizziness, drowsiness and respiratory depression following acute inhalation or oral exposure (GOV.UK, 2024g). Toluene has an EAL of 8000 µg/m^3 as a one-hour mean and 260 µg/m^3 for one week (long term), and an EQS value in freshwater of 74 µg/l as an annual average. Xylene can be harmful if it comes into contact with skin or via inhalation exposure; however, low-level exposure (inhalation, oral, dermal exposure) is not expected to lead to adverse health effects (GOV.UK, 2024h). Xylene has an EQS value for freshwater of 30 µg/l. There is no limit value under the Air Quality Standards, but it has a long-term inhalation DNEL of 65.3 mg/m^3 for systemic effects for long-term exposure (ECHA, n.d.(c)).

6.2.3 Synthetic diesel (FT-diesel and e-diesel)

There are potential differences in the composition of synthetic diesel compared to its fossil fuel equivalent. As discussed in Section 7.4, EN 15940 synthetic diesel is entirely paraffinic and does not contain aromatics, whereas its fossil fuel equivalent can typically contain around 25% m/m aromatics (Concawe, 2017).

Conventional diesel can contain up to 25% aromatic compounds (with up to 11% w/w PAHs); however, the composition can vary depending on the geographical source of the fuel (GOV.UK, 2025d). Other aromatics that could be present in diesel fuel include benzene, toluene and xylene (IARC, 1989). The risks to human health for these substances are discussed in Section 6.2.1. Exposure to PAHs can irritate eyes and breathing passages with some PAHs also being considered as carcinogens (Centers for Disease Control and Prevention, 2009). Benzo(a)pyrene, which is used as a marker for PAHs, has a target value of 1 ng/m^3 in air (GOV.UK, 2025b).

6.2.4 Ammonia

There are not expected to be differences in the composition of biomethane and e-methane and its fossil fuel equivalent as further discussed in Section 7.5. The risk to human health from ammonia is discussed in Section 6.2.4.

6.3 Summary

This section demonstrates that there could be potential human health risks from the release of pollutants during the production of alternative fuels. Exposure can be via air or water.

Seven key pollutants have been identified which could give rise to human health risks, namely hydrogen, methane, ammonia, carbon oxides (carbon monoxide and carbon dioxide), particulate matter, hydrogen sulphide, and nitrogen oxides. Emissions to land through waste can also contain substances hazardous to human health. However, only a hazard-based assessment could be performed since there is limited information in the literature. Information is required for emission levels and RMMs in place, but many of these plants are not yet in operation.

The alternative fuels have been compared with conventional fuels to identify any new pollutants and their potential hazards to human health in the fuel products. There is expected to be no difference for biomethane and methane, but some differences for sustainable aviation fuels. For example, benzene, toluene and xylene are added to synthetic paraffinic kerosene with aromatics. Benzene is carcinogenic, toluene can lead to dizziness, drowsiness and respiratory depression, and xylene exposure can be harmful.

Novel pollutants have also been identified which could be emitted during the production of the alternative fuels. This includes lignin (not classified for human health) and ethanol, which can lead to mood changes, slurred speech, nausea and uncoordinated movements. Further research is required for novel pollutants, as in some cases only a general description of the composition is available in the literature.

7 Physicochemical Properties

This section outlines the physicochemical properties of the alternative fuels under consideration in this study. These properties were collated from publicly-available literature, safety data sheets and relevant fuel standards.

Ricardo hosted a workshop on behalf of the Environment Agency to validate and supplement the findings reported below. The workshop was attended by 70 industry stakeholders and included representatives from organisations directly involved in the production of the alternative fuels under consideration in this study. Specific requests were made to the attendees for the provision of more precise data (compared to that specified in fuel standards as below), as well as data on properties relating to how the fuels under consideration interact with the environment. Feedback from this group was that such data is unlikely to be available due to the nascency of the industry. Furthermore, where such properties are measured by fuel producers, the results are considered proprietary and are not typically made publicly available. The consensus from the group was that the approach described below, which utilises properties from fuel standards, was the most appropriate.

The alternative fuels discussed in this section can be split into two broad categories. The first category consists of fuels comprising a single molecular entity, such as ammonia (NH_3) and biomethane (methane, CH_4). As a singular molecular entity, their properties are consistent and well-defined, and are reported as discrete values. It is important to recognise that the ammonia and biomethane produced for use as fuel are chemically identical to those produced as commodity chemicals, which have been being produced and traded globally for decades. Therefore, any processes or procedures relevant to the handling, storage and incident management of these chemicals at present are transferable to the respective novel fuels.

The second category of fuels are “distillate” fuels, such as SAF and renewable diesel, which comprise mixtures of molecules. The bulk properties of the fuel depend on the exact molecular composition, which can be variable. As with fossil fuels, this class of alternative fuels is typically produced to industrial standards, where the properties of the fuel must be within a defined range before it can be sold on the market. The properties of these fuels are reported as ranges.

7.1 Properties reported

The following fundamental properties were identified for all alternative fuels where available:

- Melting point
- Boiling point
- Density at ambient temperature
- Density at temperature of use
- Viscosity at ambient temperature

- Viscosity at temperature of use
- Vapour density
- Water solubility
- Vapour pressure
- Autoignition temperature
- Flash point
- Flammability limits in air
- Explosive limits
- Net calorific value

For the “distillate”-type alternative fuels, various fuel-specific properties have been identified, including, for example, distillation properties, cloud point, sulphur content, water content and cetane number. These are properties historically used to characterise fossil diesel and kerosene, and are not applicable to ammonia or biomethane.

The following properties relating to the environmental fate of alternative fuels were also collected where available:

- Octanol-water partition coefficient
- Organic carbon-water partition coefficient
- Henry’s Law Constant
- Soil-water partition coefficient
- Diffusion coefficients in air and water
- Abiotic and biotic half-lives in soil and water

All properties are reported to the number of decimal places given in the primary literature source.

7.2 Biomethane and e-Methane

Chemical Name: Methane
Chemical Formula: CH_4
CAS Number: 74-82-8
State at room temperature: Gas

Biomethane is typically either liquified or compressed before being used as a transport fuel. The properties specified in Table 45 at -161°C pertain to biomethane being used as a fuel in its liquid state at atmospheric pressure. The properties of biomethane and e-methane are identical to those of fossil methane.

Table 45. Physicochemical properties of biomethane and e-methane

Property	Reported Value	Source
Melting point (°C)	-183	International Labour Organization and World Health Organization (2000)
Boiling point (°C)	-161	International Labour Organization and World Health Organization (2000)
Density at 25°C, 1 atm (kg/m^3)	0.6567	Air Liquide (2024a)
Density at -161°C, 1 atm (kg/m^3)	422.36	Air Liquide (2024a)
Viscosity at 25°C (Pa·s)	n/a	
Viscosity at -162°C (Pa·s)	1.46×10^{-4}	CAMEO Chemicals (1999)
Relative Vapour density (air = 1)	0.6	International Labour Organization and World Health Organization (2000)
Vapour pressure at 25°C (kPa)	62182	UKHSA (2024)
Flash point (°C)	n/a	
Autoignition temperature (°C)	537	International Labour Organization and World Health Organization (2000)
Flammability limits (vol% in air)	5.3–14	National Research Council (US) Committee on Toxicology (1984)
Explosive limits (vol% in air)	5.53–15	UKHSA (2024)
Lower heating value (MJ/kg)	49.00	DESNZ (2024a)
Water solubility at 25°C (mg/L)	22	UKHSA (2024)
Partition coefficient n-octanol/water (Log Kow)	1.09	International Labour Organization and World Health Organization (2000)

Property	Reported Value	Source
Henry's Law constant (atm-m^3/mol at 25°C)	0.7050	Sander (2023)

7.3 Sustainable aviation fuel

As outlined previously, SAF must be produced according to the ASTM D7566 (ASTM, 2024) standard, which defines the properties that SAF produced using approved pathways must meet. The approved SAF production pathways relevant to this study are:

- Fischer-Tropsch hydroprocessed synthesised paraffinic kerosene (FT-SPK)
- Synthesised kerosene with aromatics derived by alkylation of light aromatics from non-petroleum sources (FT-SKA)
- Alcohol to Jet Synthetic Paraffinic Kerosene (AtJ-SPK)
- Synthetic Paraffinic Kerosene with Aromatics (AtJ-SKA)

The property requirements for each of these SAFs from ASTM D7566 are provided in Table 46 (ASTM, 2024). The recommended target properties for fuel producers evaluating potential SAFs for ASTM D4054 approval are also presented as an indicative assessment of the required properties for SAF (ASTM, 2024).

Generally, SAF must be blended with conventional aviation fuel (Jet A-1) prior to use in aircraft to ensure safe and reliable aircraft operation. This blending aligns the fuel's properties with those of Jet A-1, the fuel standard to which aircraft and engines are typically designed to operate. The properties of conventional jet fuel and SAF blends, as defined in ASTM D7566, fall within the specified property limits for Jet A-1, as detailed in Table 46. Therefore, while Table 46 does not specify properties for all SAFs, they are unlikely to differ significantly from the Jet A-1 standard.

The existence of a fuel standard for SAF means that, despite various feedstocks and production pathways, their physicochemical properties must be within the range defined in the standard. Therefore, their observed properties will be similar, though the molecular composition may differ. SAF trace composition, such as sulphur content, is strictly regulated by fuel standards due to the significantly higher safety concerns and the broader range of performance requirements in aviation (e.g., operation at altitude) compared to other transport modes (US Department of Energy, 2020).

To guarantee fungibility, the properties specified for SAF are generally within the range expected for Jet-A1. Both SAF and fossil jet fuel comprise aromatics, cycloalkanes, iso-alkanes and n-alkanes. The presence of oxygenated molecules, heteroatom-containing molecules, olefins and metals is not permissible, as they have detrimental effects on the required fuel properties (US Department of Energy, 2020). The most significant variation in

molecular composition for the SAFs considered in this study is the aromatic content, although the FT-SPK and AtJ-SPK pathways do not produce aromatic molecules.

As noted above, feedback from stakeholders consulted during this study suggested that detailed physical and chemical properties of SAF are often commercially sensitive and are unlikely to be made available publicly. Consequently, the fuel standards reported in Table 46 constitute the best available information on the properties of SAF. Furthermore, as properties that relate to the fate of SAF in soil and water are not defined by fuel standards, very limited information on these properties is available. Future research into this area will be important to help understand exactly how SAF behaves in the environment if released.

Table 46. Property specifications for Jet A-1 (ASTM D7566), recommended target properties for SAF (ASTM D4054), and property specifications for currently approved SAF (ASTM D7566). n/a = not applicable, n/s = not specified

Property	Jet A-1	Target Properties	FT-SPK	FT-SKA	AtJ-SPK	AtJ-SKA
Blending limit (%v/v)	n/a	n/a	50	50	50	100
Acidity, total mg KOH/g	<0.10	<0.015	<0.015	<0.015	<0.015	<0.015
Aromatics, volume percent (vol%)	8–26.5	n/s	n/s	<21.2	n/s	8–20
Aromatics, mass percent (wt%)	n/s	<20	<0.5	<20	<0.5	n/s
Sulphur, mercaptan, mass percent	<0.003	n/s	n/s	n/s	n/s	n/s
Sulphur, total mass percent	<0.30	n/s	n/s	n/s	n/s	<0.0015
Distillation temperature (°C):						
10% recovered, temperature (T10)	<205	150–200	<205	<205	<205	<205
Final boiling point	<300	195–296	<300	<300	<300	<300
Distillation residue, percent	<1.5	<1.5	<1.5	<1.5	<1.5	<1.5

Property	Jet A-1	Target Properties	FT-SPK	FT-SKA	AtJ-SPK	AtJ-SKA
Distillation loss, percent	<1.5	<1.5	<1.5	<1.5	<1.5	<1.5
Flash point (°C)	>38	38–66	>38	>38	>38	>38
Density at 15°C (kg/m^3)	775–840	730–880	730–770	755–800	730–770	775–840
Freezing point (°C)	<-40	<-40	<-40	<-40	<-40	<-40
Viscosity at -20°C (mm^2/s)	<8.0	<12	n/s	n/s	n/s	n/s
Net heat of combustion (MJ/kg)	>42.8	n/s	n/s	n/s	n/s	n/s
Copper strip, 2 h at 100°C	1	n/s	n/s	n/s	n/s	n/s
Water content (mg/kg)	n/s	<75	<75	<75	<75	<75
Sulphur (mg/kg)	n/s	<15	<15	<15	<15	<15
Cetane number	n/s	35–60	n/s	n/s	n/s	n/s
Partition coefficient n-octanol/water (Kow) (SASOL, 2018)	n/s	n/s	>6.5	n/s	n/s	n/s

7.4 Synthetic diesel (FT-diesel and e-diesel)

Chemical Formula: Unknown
CAS Number: n/a
State at room temperature: Liquid

To be used in road transport in the UK, synthetic diesel must conform to the properties specified in the BS EN 15940 (European Standards, 2023) standard for paraffinic diesel fuel from synthesis or hydrotreatment, as shown in Table 47. This standard applies to all synthetic diesel fuels. Although various feedstocks and conversion processes can be used to produce synthetic diesel, their physicochemical properties must be within the range defined in Table 47. Similarly, while not yet commercially developed, diesel produced by pyrolysis or hydrothermal liquefaction would also have to conform to these properties.

For comparison, BS EN 590 (British Standards Institution, 2024), the standard applicable to conventional diesel fuel containing up to 7% FAME, is also shown in Table 47. Synthetic diesels, i.e. FT-diesel, e-diesel and HVO, are drop-in fuels. This means that they are fully fungible with fossil diesel and are not subject to blending limits, as is the case with FAME.

Properties regarding the fate of synthetic diesels in soil and water are not defined by fuel standards. Furthermore, public domain data is limited, since FT-diesel and e-diesel are not yet produced at a significant scale industrially.

Table 47. Properties for synthetic diesel defined in BS EN15940 and conventional diesel defined in BS EN 590. n/s = not specified

Property	BS EN 15940	BS EN 590
Density at 15°C, 1 atm (kg/m^3)	0.770–0.790	0.820–0.835
Viscosity at 40°C (mm^2/s)	2.0–4.0	2.0–4.5
Sulphur Content (mg/kg)	<5	<10
Flash Point (°C)	>70	>56
Cloud Point, Summer (°C)	<-15	<3
Cloud Point, Winter (°C)	<-34	<-15
Cold filter plugging point, Summer (°C)	<-15	<-5
Cold filter plugging point, Winter (°C)	<-34	<-15

Property	BS EN 15940	BS EN 590
Water Content (mg/kg)	<200	<200
Ash Content (%m/m)	<0.001	<0.01
Initial boiling point (°C)	>180	n/s
Distillation (recovery at 250°C; %v/v)	<65	<65
Distillation (recovery at 350°C; %v/v)	>85	>85
Cetane number	>70	>51
Cetane index	>70	>46
Oxidation stability (g/m^3)	<25	<25
Copper strip corrosion 3 h at 50°C	<1	1
Lower heating value (MJ/kg)	>42	n/s
Particulate matter (mg/kg)	<10	<24
FAME (%v/v)	0	<7
Total aromatics (%m/m)	0	n/s
Polycyclic aromatics (%v/v)	<0.02	n/s
Polycyclic aromatics (%m/m)	n/s	<8

7.5 Ammonia

Chemical Name: Ammonia, anhydrous
Chemical Formula: NH_3
CAS Number: 7664-41-7
State at room temperature: Gas

Ammonia is typically either liquified or compressed before being used as a transport fuel. The properties specified in Table 48 at -33.5°C pertain to ammonia being used as a fuel in its liquid state at atmospheric pressure. The properties of green ammonia are identical to those of fossil ammonia.

Table 48. Physicochemical properties of ammonia

Property	Reported Value	Source
Melting point (°C)	-77.7	Environment Agency (2007)
Boiling point (°C)	-33.5	Environment Agency (2007)
Density at 25°C, 1 atm (kg/m^3)	0.7033	Air Liquide (2024b)
Density at -33.5°C, 1 atm (kg/m^3)	681.8	National Institutes of Health (2024)
Viscosity at -33.5°C (Pa·s)	2.55×10^{-4}	National Institutes of Health (2024)
Vapour density (air = 1)	0.5967	National Institutes of Health (2024)
Vapour pressure at 20°C (kPa)	1013	International Labour Organization and World Health Organization (2013)
Flash point (°C)	n/a	
Autoignition temperature (°C)	630	International Labour Organization and World Health Organization (2013)
Flammability limits (vol % in air)	15–28	IEA-AMF (2024)

Property	Reported Value	Source
Explosive limits (vol% in air)	15–33.6	International Labour Organization and World Health Organization (2013)
Lower heating value (MJ/kg)	18.6	IEA-AMF (2024)
Water solubility at 20°C (mg/L)	531,000	Environment Agency (2007)
Partition coefficient n-octanol/water (Log Kow)	0.23	Environment Agency (2007)
Henry's Law constant (atm-m^3/mol at 25°C)	1.61×10^{-5}	Environment Agency (2007)

7.6 Impact of property variations on combustion emissions

The above discussion highlights that the physicochemical properties of synthetic diesel and SAF differ from their fossil analogues. This can impact the emissions that occur during combustion of these fuels. This section considers the potential impact of these differences on emissions when the alternative fuel is used in sectors regulated by the Environment Agency. As transport is not regulated by the Environment Agency, the discussion focuses on synthetic diesel, which could be used in some industrial sectors such as in back-up or mobile generators.

The most significant compositional difference between synthetic and fossil diesel is that EN 15940 synthetic diesel is entirely paraffinic and does not contain aromatic molecules (European Standards, 2023). Conversely, EN 590 fossil diesel, although not specified in the standard, typically contains around 25% m/m aromatics (Concawe, 2017). The paraffinic nature of synthetic diesel fuels generally results in a significantly higher cetane number than fossil fuels (IEA-AMF, 2017).

The high cetane number of synthetic paraffinic diesel fuels (>70, vs >51 for fossil fuels, see Table 47), combined with their lower density and viscosity (see Table 47) result in an increase in the chemical reactivity of the fuel under combustion conditions relative to fossil diesel. This can result in more efficient combustion, leading to lower carbon monoxide (CO) and unburnt hydrocarbon emissions, with reductions of up to 40% having been demonstrated under optimal engine conditions (IEA-AMF, 2017). Reductions in PM formation of 30–55% have also been reported for paraffinic diesel (IEA-AMF, 2017).

It should be noted that the above findings relate to the application of synthetic diesels in diesel combustion engines for transport. We have been unable to identify any studies relating to non-CO_2 emissions from the use of synthetic diesel in stationary generators or industrial applications. However, in Ricardo's view, the general principles described above are likely to be appliable to the use of synthetic diesels in sectors regulated by the Environment Agency. Specifically, the chemical composition of paraffinic diesels offers potential reductions in CO, unburned hydrocarbon and PM emissions, with the magnitude of these reductions depending on the engine conditions.

8 Incident Management

8.1 Introduction

This section outlines key considerations for developing robust incident management strategies for alternative fuels. These strategies apply to production sites, the fuel supply chain (including transportation and storage), and end users.

Chemical incident management aims to minimise, mitigate and manage the impact of a chemical release or reaction. Effective incident management takes a rounded approach to multiple phases of an incident. It starts with planning and preparedness to ensure that all potential risks have been considered and effective response plans are in place, along with appropriate equipment, training and integration of all parties who may be required to act in a response event. The next phase is the incident response itself, involving the deployment of personnel to take steps to control risks to people and the environment when an incident occurs. The final phase is recovery and remediation, where contamination is removed, and the affected area returned to normal (HSE, 2015a).

Chemical incident response management operates in a regulated environment, with a number of UK regulations covering environmental impacts from chemical incidents. This includes The Environmental Permitting (England and Wales) Regulations 2016 and The Control of Major Accident Hazards Regulations 2015.

The Environment Agency and the Health and Safety Executive are the competent authorities for COMAH in England. Regulatory oversight is provided to high-hazard industries storing dangerous substances in quantities that fall within the scope of the Regulations. The Environment Agency assesses safety reports and accident prevention policy including off-site emergency plans. They also undertake inspections at COMAH sites and are responsible for investigating accidents and conducting enforcement where required (Environment Agency, 2025b).

The Environment Agency is also the competent authority for The Environmental Permitting (England and Wales) Regulations 2016, again providing regulatory oversight and investigation for accidents and subsequent enforcement.

This report aims to highlight key incident management factors to be considered in the development of incident management plans and actions at sites storing alternative fuels. It is not intended to be comprehensive or to serve as direct guidance on the implementation of incident management policy at these sites.

Similarities and differences in incident management considerations between alternative fuels and fossil fuels are highlighted to provide insight into key factors for developing incident management plans. Since individual site plans depend on a range of variables, this report offers an introduction to the physicochemical properties of alternative fuels that influence incident response strategies. It does not provide specific guidance for developing site-specific plans.

This section considers fuels in the following groupings:

- Ammonia
- Biomethane and e-methane
- Synthetic liquid light oils
    - Synthetic Diesel
    - e-Diesel
    - Diesel from pyrolysis
    - Diesel from hydrothermal liquefaction
- Sustainable Aviation Fuel
    - Fischer-Tropsch hydro-processed synthesised paraffinic kerosene (FT-SPK)
    - Synthesised kerosene with aromatics derived by alkylation of light aromatics from non-petroleum sources (FT-SKA)
    - Alcohol to jet synthetic paraffinic kerosene (AtJ-SPK)
    - Synthetic Paraffinic Kerosene with Aromatics (AtJ-SKA)

For each group of fuels, the key physicochemical properties that influence environmental behaviour are reviewed first. This is followed by a discussion of appropriate incident management techniques. Where the properties of an alternative fuel are sufficiently similar to those of a fossil fuel that existing response approaches are applicable, this is specifically noted.

8.2 Relevance of physicochemical properties to Incident Management operations

Table 49 provides an overview of the relevance of physicochemical properties to specific tasks or processes within the response to an incident.

Table 49. Relevance of physicochemical properties to Incident Management Operations, where "X" denotes relevance

Operation	Aspect	Option	Physicochemical Property										
			Melting point	Boiling point	Density	Viscosity	Vapour density	Vapour pressure at 20°C	Flash point	Autoignition temperature	Flammability limits	Water solubility	Partition coefficient n-octanol/water (Log Kow)
Containment	Effectiveness of primary containment	Storage tank/vessel	X	X	X			X	X				
		Piped containment	X	X	X	X		X	X				
		Transportation tank/vessel	X	X	X	X		X	X				
	Effectiveness of secondary containment	Fixed bund		X	X		X	X			X	X	
		Temporary bunding		X	X		X	X			X	X	
		Interceptor		X	X			X				X	
		Oil/water separator		X	X							X	
		Isolation tank		X		X		X					

Operation	Aspect	Option	Physicochemical Property										
			Melting point	Boiling point	Density	Viscosity	Vapour density	Vapour pressure at 20°C	Flash point	Autoignition temperature	Flammability limits	Water solubility	Partition coefficient n-octanol/water (Log Kow)
	Effectiveness of tertiary containment	From drainage		X		X						X	
		In/On water			X			X				X	
Recovery	Selection of pumps		X	X	X	X			X				
	Removal options	Ground skimmers	X										
		Water skimmers	X	X		X						X	
		Absorbent material	X	X								X	
Fire	Firefighting strategy				X				X	X	X	X	
	Extinguishing media				X				X	X	X	X	
	Impact on fire water				X			X				X	X

Operation	Aspect	Option	Physicochemical Property											
			Melting point	Boiling point	Density	Viscosity	Vapour density	Vapour pressure at 20°C	Flash point	Autoignition temperature	Flammability limits	Water solubility	Partition coefficient n-octanol/water (Log Kow)
Monitoring	Indication of release				X	X		X	X				
	Air monitoring			X			X	X					
	Water monitoring											X	
	Flammable atmosphere monitoring			X			X	X	X		X		

8.2.1 Containment

In the event of a fuel release, incident management actions require a focus on control and containment of the product. Containment options fall into three categories:

- Primary containment – The intended means of holding the fuel; for example, tanks, pipes and transportation containers.
- Secondary containment – The second line of defence for controlling released fuels, with the intention of retaining the spillage on-site; most commonly bunding.
- Tertiary containment – Aims to minimise the impact of a release where the primary and secondary measures of containment have failed. This can include drainage systems and booms (HSE, 2015b).

Inherent chemical compatibility influences the selection of materials used in the design and construction of containment systems. The physicochemical properties of the released fuel also affect the choice of secondary and tertiary containment measures and their effectiveness.

For secondary containment, the physical state of the released fuel influences how the fuel behaves once so confined. Solids and liquids with high boiling points, such as fossil and synthetic diesel fuels, can be held effectively in secondary containment. However, more volatile liquids, with their low boiling points and high vapour pressure (for example fossil and sustainable aviation fuels), evaporate, which influences the effectiveness of secondary containment.

The flammability of materials in secondary containment also requires consideration. Materials with lower flash points have the potential to create flammable atmospheres. The HSE defines flammable liquids as liquids with flash points of 60°C or below (HSE, 2025). Similarly, a lower flammability limit indicates a higher risk, as only small amounts of vapour are required for ignition. A vapour density greater than air also indicates the potential for vapours to travel at ground level to reach ignition sources, leading to a fire event.

Where tertiary containment is required, the fuel's physical state and flammability remain key considerations. Water solubility and density are also critical when evaluating interceptor systems. Highly water-soluble fuels cannot be contained as effectively, as they can dissolve and bypass the system. For non-soluble fuels, density determines whether the material will float or sink in water, influencing both containment and recovery strategies.

8.2.2 Recovery

Following secondary and tertiary containment, incident management actions move to the recovery of spilled material. The physical state of materials is important. For liquid spills, the viscosity and density of the material influence the selection of appropriate pumps. For example, liquids with higher viscosities require higher pressure peripheral pumps.

Corrosive properties are also relevant due to potential interactions between the fuel and the pump and piping construction materials.

The utilisation of submersible pumps is restricted to insoluble fuels with a higher density than water.

8.2.3 Fire

Assessments of fire risk are required through all phases of incident management. The risk of fire from the fuels is indicated through the autoignition temperature, flash point and flammable / explosive limits of the fuels.

In the event of a fire, firefighting strategy decisions depend on a range of factors at the incident, including the location and quantities of fuels involved and the potential for re-ignition. The flammability properties mentioned above are also relevant to strategy decisions.

The selection of extinguishing media is influenced by water solubility and density. The choice of foam or water media depends on the water solubility and density of the fuel, as there is a risk of an insoluble fuel with a density lower than water continuing to burn whilst floating on fire water. Foam can also be utilised to reduce the evolution of flammable vapours from fuels with high vapour pressures (HSE, 2015c).

The water solubility and density indicate the level of severity of fire water contamination. Highly water-soluble fuels are likely to result in increased contamination, while for non-soluble materials, the density indicates whether residual fuel will sit above or below fire water.

8.2.4 Monitoring

Monitoring is utilised in both the initial detection of fuel releases and the subsequent evaluation of pollution location and levels. The physical state of the fuel both in primary containment and after release influences the choice of detection methods. Volatility and density are also relevant in understanding the potential for evaporation and how the resultant gas will behave when released to air. Water solubility and density are relevant for monitoring releases to water. Finally, the chemical composition of the fuel influences the type of monitoring technique that is most applicable.

8.3 Ammonia

8.3.1 Physicochemical properties and behaviour in the environment

The most important physicochemical properties for ammonia for incident management are its melting (-77.7°C) and boiling (-33.5°C) points (Table 48). Ammonia is typically stored in a liquified form by compressing it or cooling it below its boiling point (Fertilizers Europe, 2014). Industrial ammonia systems vary in volume and pressure specifications, with liquefied ammonia storage typically operating at its standard vapour pressure (101.3 kPa) (Fertilizers Europe, 2014).

8.3.1.1 Behaviour of leaks and spills

If there is a loss of containment of liquified ammonia, the reduction in pressure and/or increase in temperature results in ammonia undergoing a phase transition from liquid to gas. Therefore, incident management strategies need to consider the control of gaseous ammonia. Specific incident scenarios influence the pathway of phase transition from liquid ammonia to ammonia gas.

Liquid ammonia spills typically result from catastrophic failures of containment leading to substantial product loss. Several factors influence spill development and vapour generation:

- Release rate
- Heat transfer characteristics between the liquid and contact surfaces
- Substrate porosity and absorption capacity
- Ambient ventilation conditions and wind speed
- Temperature of both substrate and surrounding air

The confined nature and dimensions of the spill area directly correlate with the severity and rapidity of effects (Griffiths & Kaiser, 1982).

With storage tank failures, there is typically an initial sudden vapour release, coinciding with a pressure drop. This is followed by a steady-state vapour generation phase as the liquid contacts and cools surrounding surfaces. Liquid ammonia releases typically generate significant volumes of ammonia in the initial stages of an incident, with an expansion ratio of around 1:850 when transitioning from the liquid to gaseous phases (OSHA, n.d.).

The release rate is the primary determinant of whether liquid ammonia will be dispensed, with higher rates increasing the likelihood, particularly when the liquid is under pressure.

When liquid ammonia is released to atmospheric conditions, auto-refrigeration occurs. As the liquid evaporates, it absorbs thermal energy from its surroundings due to its high latent heat of vaporisation (Air Liquide, n.d.). This process initially cools the pooled liquid to its boiling point (-33°C), but experimental evidence demonstrates that temperatures can decrease substantially further, with recorded values as low as -67°C (Corruchaga et al.,

2022). Cooling ammonia to well below its boiling point leads to a reduced evaporation rate which increases the persistence of the hazard. This presents cold hazards for emergency responders in addition to the corrosive properties of the substance. For example, following the derailment of a freight train transporting ammonia, close to Minot, North Dakota USA, vapour ammonia clouds persisted at low levels and were carried by the wind towards the populated area, leading to approximately 11,600 people needing to take protective actions (NTSB, 2002).

8.3.1.2 Behaviour in air

Although ammonia is naturally less dense than air at ambient temperatures, with a density of approximately 0.70 kg/m³ at 25°C and a relative vapour density of 0.5967 compared to air (see Table 48), its behaviour during a release is influenced by other important physical properties. When ammonia is released from a high-pressure system into the atmosphere, a thermodynamic decompression occurs, causing rapid cooling of the gas. This cooling effect can make the ammonia temporarily denser than air, leading it to remain close to the ground.

The extent of cooling depends on the rate at which the gas is released from the storage system, with faster releases causing greater temperature drops. As the ammonia vapour warms, it regains its natural characteristic of being lighter than air and tends to rise and disperse in open environments. Where appropriate, allowing ammonia to dissipate into the atmosphere is considered one of the safest response strategies.

However, in an indoor environment with limited ventilation, increased concentrations of ammonia gas may occur.

8.3.1.3 Behaviour in water

Liquid ammonia is less dense than water, with a density of 681.8 kg/m³ at −33.5°C and 1 atmosphere pressure (see Table 48). It has a very high solubility in water, approximately 531,000 mg/L at 20°C, and is highly hydrophilic. When released, ammonia partitions into the water phase and, upon dissolving, forms ammonium hydroxide. This compound is a strong alkali that can increase the pH of contaminated water. Ammonia gas also readily dissolves into bodies of water and can dissolve into water vapour in humid conditions. This process often produces a visible white vapour cloud, as was observed during a major ammonia release in Dakar, Senegal in 1992 (Dharmavaram & Pattabathula, 2022).

8.3.1.4 Flammability

Ammonia’s autoignition temperature, the temperature at which it spontaneously ignites without an external ignition source, is 630°C. When managing incidents involving ammonia releases, it is important to also consider its flammability limits to evaluate the fire risk. As reported in Table 48, ammonia’s flammability limits in air are between 15 and 28 volume percent, while its explosive limits range from 15 to 33.6 volume percent.

Although ammonia is not classified as a flammable gas, it can form flammable and explosive mixtures with air at these concentrations. The lower flammability threshold for

ammonia is higher than that of many hydrocarbon gases (for example, methane has a lower explosive limit of 5%), meaning that a much higher concentration of ammonia gas is needed to create a flammable atmosphere than for methane. Nonetheless, the potential for ignition of ammonia releases remains a critical consideration in incident management.

8.3.2 Incident management

8.3.2.1 Spills and leaks

As outlined in Section 8.2.1, ammonia releases may occur in both liquid and gaseous phases. Such incidents present an immediate health risk to on-site personnel and emergency responders and may also necessitate off-site precautions to protect downwind populations. Due to its acute toxicity, corrosive nature, and potential flammability, an initial exclusion zone is required, along with the deployment of specialist personal protective equipment. This includes appropriate respiratory protection and protection for the skin and eyes (NCEC, 2025). To illustrate the levels at which ammonia poses a health hazard, the UK 8-hour Workplace Exposure Limit for ammonia is 25ppm and the short-term 15-minute level is 35ppm (HSE, 2020).

The overall incident management strategy should take into account the presence of downwind populations and include provisions for monitoring atmospheric concentrations to determine whether a shelter-in-place or evacuation strategy is appropriate. It should also consider the potential need to close transportation routes, such as roads and railway lines, to limit exposure and ensure public safety. The use of ammonia as a fuel leads to it being stored and handled in locations where it has not traditionally been present, which increases the importance of proactive planning and risk assessment in these new settings.

Standard leak-monitoring techniques are applicable for detecting a release of ammonia. These range from monitoring for ammonia concentrations in air, through to flow rate and capacity meters. As detailed below, rapid secondary containment of ammonia is critical to the mitigation of environmental impacts. Off-site impacts are likely to occur in a greater variety of settings than for fossil fuels, and first responders may be less familiar with incident management options.

Incident management options once primary containment has been lost are considered below.

8.3.2.1.1 Containment of gaseous releases

The high water solubility of ammonia leads to water curtains being an effective measure for containing a release of gas. Research by the Institution of Chemical Engineers (IChemE) demonstrates that water curtains can capture up to 95% of ammonia vapour when properly configured with an appropriate droplet size and spray pattern (Schoten et al., 2000). Therefore, water curtains at sites handling and storing ammonia provide an effective secondary containment strategy. However, careful planning for containing the water is required, since aqueous solutions of ammonia have an alkali pH and the potential

to be corrosive, as previously detailed. This is equally relevant where water curtains are used as an emergency protective measure, for example to protect a downwind location.

An alternative strategy is to place a physical barrier such as a tarpaulin over the release. This has the effect of limiting the spread of ammonia gas and the potential for released gas to condense into liquid ammonia (Ng & Ming, 2024). Temporary bunding or damming can be utilised to collect the liquid. Water can also be added to the dammed/bunded area to increase the collection of ammonia gas. Collection and appropriate disposal of the resultant liquid are required when using this containment technique.

8.3.2.1.2 Containment of liquid releases

Large releases of ammonia have the potential to be in the liquid phase. Bunding is suitable to control a liquid release, recondensed gaseous leaks and contaminated water used in the water curtain collection of gas releases. Both permanent and temporary bunding are applicable. The low temperature of a liquid ammonia release and its high water solubility are important considerations for the location and materials used in any temporary bunding. Concrete brick and stone with an impervious floor can be considered for permanent bunding construction. Earth dyke is possible for temporary bunding (Fertilizers Europe, 2014).

For recovery of contained liquid ammonia and ammonia solutions from bunded areas, the corrosive properties of ammonia solutions are important in the selection of pumping equipment and reception containers. This is particularly applicable for on-site pumping equipment utilised by emergency responders or specialist clean-up teams, both on- and off-site.

Contained small spills and residual contaminated water can be collected effectively using standard chemical absorbents.

Sites may also utilise ammonia dump tanks where ammonia from primary containment can be transferred to a dump tank containing water which will dissolve it. Where available, liaison with site staff on the applicability of dump tank utilisation should be considered.

Where water has been used as part of a secondary containment strategy, interceptors are ineffective in the collection/removal of ammonia. Ammonia is highly water soluble and remains in the aqueous phase in the interceptor system. Where the flow of contaminated water to an interceptor system is inevitable, isolation of the interceptor is the prime option to prevent further off-site pollution. If the capacity of the interceptors is insufficient, the contents require transfer to alternative containment.

In all cases described above, any contaminated water requires assessment for specialist hazardous waste disposal.

Ammonia’s high solubility in water presents a challenge for tertiary containment. Contaminated water released to any drainage system presents an environmental risk, with isolation of the drain system sometimes being the best option to prevent further contamination.

Where contamination of off-site water or soil has occurred, there are limited options for collection due to its high solubility. Actions to consider include preventing further contamination by isolating the source, containing released material and isolating contaminated drainage systems where possible. Monitoring the levels of ammonia and ammonium hydroxide can also provide an indication of risk levels.

8.3.2.2 Releases to controlled waters

As discussed above, dissolution occurs upon release of ammonia to water, resulting in rising pH levels as ammonium hydroxide is formed. With continued release into the water system and a further elevation of pH, free or unionised ammonia can also exist. Both effects represent a high level of risk to aquatic ecosystems (ITOPF, 2024).

Once released to controlled waters, there are limited options for removing the ammonia. Therefore, containment at the secondary and tertiary levels is critical.

Monitoring pH using standard methods can provide an indication of the presence of ammonia, with higher pH readings likely to indicate higher levels of contamination. Specific aqueous monitoring equipment for ionised and unionised ammonia is available.

The use of ammonia as a fuel is likely to result in its storage and use in new locations, such as ports when it is used as a marine fuel. This will introduce the potential for release into a wider range of environments than the current industrial and agricultural uses of ammonia.

8.3.2.3 Fire

As discussed in the physical properties section, ammonia is not classified as a flammable material but does have the potential to combust, with a flammable range of 15–20% by volume in air (Table 48). Whilst its use as a fuel is a new application, ammonia is utilised extensively in the chemical manufacturing and agricultural sectors and for refrigeration purposes. Firefighting strategies and the selection of appropriate extinguishing media are therefore well established. It is possible that the introduction of ammonia fuel storage in alternative locations may mean that the local Fire Service responders are less familiar with the fire response for ammonia.

Water is the most appropriate extinguishing media and is also effective in ammonia vapour suppression. However, the containment of fire run-off water is required, as discussed in the containment section above.

8.4 Biomethane and e-methane

8.4.1 Physicochemical properties and behaviour in the environment

Biomethane and e-methane have identical physicochemical properties to fossil methane (see Section 7.2). Therefore, established techniques for the management of incidents involving fossil methane are also applicable to those involving biomethane or e-methane.

Biomethane and e-methane are often injected directly into the gas grid close to where they are produced. If this is not the case, then they need to be stored and transported in the form of either liquid or compressed gas. Liquifying methane is costly, so bulk storage and transportation of compressed biomethane may be more prevalent.

Incident management for methane should emphasise the effectiveness of primary and secondary containment methods, as these are the most reliable means of overall control. Additional safety considerations are necessary due to the inherent risk of methane forming flammable gas mixtures that may ignite if an ignition source is present.

8.4.1.1 Behaviour of leaks and spills

Methane has a cryogenic boiling point of -161°C (Table 45). For liquefied methane, unlike ammonia, the phase change from liquid to vapour occurs immediately upon release to atmospheric conditions. The heat required to drive this rapid vaporisation is drawn from the surrounding environment, causing a significant temperature drop in the spilled liquid and nearby surfaces. Temperatures fall towards the boiling point of methane (-161°C), creating a cryogenic hazard. As a result, conditions in the immediate vicinity of the release become extremely cold and unsafe for personnel to approach without specialised protection.

The extreme temperature difference between the released liquified methane and ambient conditions leads to a substantial amount of vapour/gas production, with $1m^3$ of liquified methane at -161°C corresponding to $621m^3$ at 15°C. This production is influenced by the:

- Release rate
- Heat transfer characteristics between the liquid and contact surfaces
- Substrate porosity and absorption capacity
- Ambient ventilation conditions and wind speed
- Temperature of both substrate and surrounding air

The higher the rate of release of liquefied methane from containment, the greater the likelihood of liquid methane pooling. However, in non-catastrophic release scenarios, the formation of vapour is more likely than liquid pooling due to the rapid vaporisation of the released liquid. This vaporisation extracts heat from the surroundings, cooling the immediate area. As temperatures drop, the risk of structural damage to containment systems increases, either from material embrittlement or from the build-up and expansion of ice. If such damage occurs or low temperatures persist, liquid methane may accumulate as vaporisation slows.

Because of the extreme cryogenic temperatures involved, any pooled liquid methane is highly sensitive to the presence of water. Contact with water can trigger rapid vaporisation and, in bulk quantities, this interaction may result in an event known as a Rapid Phase Transition. This phenomenon involves the sudden conversion of liquid methane to gas, driven by the rapid heat transfer from the water, and can lead to a physical explosion. Water can also freeze at the leak point, potentially causing further damage to valves, pipework, and the walls of containers or storage vessels.

This interaction of water and liquified methane also needs to be considered by operators and Fire Services during fire events. The use of water can suppress flaming, but the introduction of water to pools of liquid methane can cause further fire development due to the generation of more flammable vapour/gas when the methane vaporises rapidly (Anay, 2006; ITOPF, 2024).

8.4.1.2 Behaviour in air

At ambient temperatures (20–25°C), methane is a vapour with a density of 0.6567 kg/m^3 and a relative vapour density of 0.6, i.e. it is lighter than air (Table 45). When methane is stored in compressed form, a loss of containment results in methane being released under pressure. In open and well-ventilated environments, the gas rises and disperses upwards into the atmosphere. However, in enclosed or partially confined spaces, methane may accumulate in the upper areas of structures, including roof voids or ceiling spaces where electrical wiring, lighting, or heating systems may be present. Thus, the buoyant nature of methane must be considered when selecting and positioning gas detection equipment, to ensure effective monitoring of potential accumulations.

As the temperature of methane vapour/gas progressively decreases (towards the boiling point), the density increases. In scenarios where there is a leak or release of liquified methane, the vapour/gas being generated will be low-lying and initially heavier than the air. The methane vapour/gas may collect and spread along the ground and in lower than ground areas until it has warmed sufficiently towards ambient temperatures.

Methane vapours can find ignition sources at distances away from the immediate source of any release. As methane vapour transitions to methane liquid, the density at the boiling point is not a practical metric for incident management. Densities of liquids are assessed with the interaction of water and possible containment options. At cryogenic temperatures such as at the boiling point of methane (-161°C), any interaction with water will cause the water to freeze, nullifying the relative assessment of behaviour between liquid methane and liquid water.

8.4.1.3 Behaviour in water

Methane has low solubility in water at 25°C (approximately 22 mg/L, Table 45), and, like most gases, its solubility decreases as temperature increases; however, its solubility will remain low at UK ambient water temperatures. In the context of incident management, the water solubility of methane has limited practical relevance. Although methane is more soluble than oxygen (which has a solubility of around 8.2 mg/L at 25°C; US Geological Survey, 2015), the likelihood of it displacing oxygen in water bodies is low. This is because methane’s buoyancy prevents it from accumulating at the water surface in sufficient concentration to drive gas exchange.

In adverse weather conditions such as rain, or when water-based vapour suppression systems are used, methane vapour in the surrounding atmosphere can dissolve into water droplets. While only limited amounts will dissolve due to its low solubility, this can

contribute to a localised dispersal of methane, reducing its concentration and helping to mitigate the risk of ignition.

Methane has an Octanol-Water partition coefficient[25] of 1.09 (Table 45), which infers that methane mixes and dissolves better in lipids than water. The partition coefficient indicates the likelihood of a substance accumulating within biological organisms. The value for methane is below the threshold value of 5 for bioaccumulation set in the Stockholm Convention for Persistent Organic Pollutants (UN Environmental Programme, 2023), and thus, it has a low propensity to bioaccumulate.

8.4.1.4 Flammability

The flammable and explosive limits (also known as 'range') are 5.3% to 14% and 5.53% to 15%, respectively. These are higher than for other fuels such as fossil petrol/diesel, propane and butane, which have ranges of around 0.9% to 11% (International Labour Organization, n.d.). Within the flammable/explosive limits for methane, the application of an ignition source will result in combustion. The hazard is reduced where methane concentrations remain outside these limits (<5.3% and >15%). Temperature also impacts the limits; higher temperatures 'raise' the upper limit and 'lower' the lower limit, widening the range over which fuel/air mixtures could combust. The effect is asymmetrical, with temperature increases having more impact on the upper limit than on the lower limit.

For methane concentrations below the 'Lower Flammable/Explosive Limit' (5.3%), the concentration needs to increase to achieve a combustible fuel/air mixture. Factors which might cause such an increase in concentration include:

- Release/production rate of methane vapour/gas
- Ventilation/wind speed
- Concentration of atmospheric oxygen
- Volumetric space of any enclosed area (the smaller the area, the greater chance of an increased concentration)

The hazard of potential combustion is reduced at concentrations above the upper limit (HSE, 2015d), but to mitigate the fire hazard completely, the concentration must be reduced to below the lower limit. This requires the concentration to transition through the flammable/explosive range.

[25] The octanol-water partition coefficient (Kow) is a measure of a substance's hydrophobicity (water solubility) and lipophilicity (fat solubility). It represents the ratio of a substance's equilibrium concentrations in two immiscible phases: octanol and water. A higher Kow value indicates that the substance is more lipophilic (solves more readily in octanol, mimicking fats) and less hydrophilic (solves less readily in water).

The autoignition temperature of methane[26] is 537°C. However, other ignition sources are also likely to be present in environments where this temperature is reached, so ignition may result from multiple potential causes.

8.4.2 Incident management

From an incident management perspective, biomethane and e-methane display identical physicochemical properties to fossil methane. Therefore, the incident management strategies used for methane are also applicable to biomethane and e-methane incidents.

8.4.2.1 Spills and leaks

As highlighted in Section 8.4.1, released methane can be present in both the liquid and gas phases, and techniques for managing each of these are described below. As for natural gas releases, there will be a fire and explosion risk, so response teams need to plan for this in their initial response. This requires cordons and a consideration of the off-site implications of a potentially flammable atmosphere.

Leak monitoring techniques for detecting a methane release are the same as for natural gas, due to the close chemical similarity of the fuels (HSE, 2004).

Secondary containment strategies for natural gas are also applicable to biomethane and e-methane and should be factored into the design of storage facilities (HSE, 2015b).

8.4.2.1.1 Gas release

Methane gas is less dense than air and will therefore disperse into the environment upon release. While methane is significantly less soluble in water than ammonia, water curtains can be employed to suppress fire risks by dispersing the gas and reducing the likelihood of ignition. Some methane molecules will dissolve in the water, so containment of the runoff water is necessary.

8.4.2.1.2 Liquid release

A liquid release of methane is possible from a loss of containment from a liquified storage vessel. Liquid methane initially evaporates to a vapour, but the energy lost in the evaporation process has a cooling effect on the spill, reducing evaporation rates and initiating an auto-refrigeration process, potentially reaching cryogenic temperatures. This introduces the risk of a rapid phase transition from the liquid to vapour phases and the emission of a shock wave. It is therefore essential to eliminate the risk of water coming into contact with liquified methane, as this could initiate the rapid phase transition. Bunding is suitable to contain a liquid methane release. Existing HSE guidance suggests that

[26] The autoignition temperature is the ignition point by which temperature is the sole ignition source required.

bunding constructed from brick/mortar or concrete is likely to have adequate resistance to most chemicals (HSE, 2015b).

Due to the cold temperature of a liquid methane spill and potentially hazardous interactions with water, interceptors are not a suitable method of secondary containment for a liquid release.

As for natural gas, biomethane/e-methane is less dense than air and will ultimately dissipate into the atmosphere, limiting the tertiary containment options available.

8.4.2.2 Release to controlled waters

Biomethane/e-methane has a low level of solubility in water, and since the gas is less dense than air, it will disperse away from water. Therefore, the risk to controlled waters is lower than for ammonia.

Standard techniques for monitoring hydrocarbon contamination of water can be utilised for biomethane/e-methane (Environment Agency, 2020).

8.4.2.3 Fire

Under fire conditions, biomethane and e-methane will behave similarly to methane. Thus, fire and explosion control will be a key aspect of incident management. The same response procedures and safety protocols used for methane incidents should be considered (UKHSA, 2024).

8.5 Synthetic liquid light oils and sustainable aviation fuel

8.5.1 Physicochemical properties and behaviour in the environment of synthetic diesel

As discussed in Section 7.4, no specific physicochemical properties of diesel produced via the Fischer-Tropsch (FT) and e-Diesel pathways were available in the literature at the time of writing. However, these diesel fuels must comply with the fuel certification standard BS EN 15940 (European Standards, 2023), which outlines the expected ranges for key properties.

FT- and e-diesel comprise n- and iso-paraffins of carbon chain lengths between C_{10} and C_{25} with almost no aromatic content (Concawe, 2022). This is comparable to fossil diesel, which typically contains C_{12} to C_{20} hydrocarbons (IEA-AMF, n.d.), but also contains 20–30 mass% aromatics (Concawe, 2017).

For properties where data is available in BS EN 15940, a comparison is made with properties specified within BS EN 590, the standard which fossil diesel must meet. In general, although there are some minor differences in the ranges for specified

physicochemical properties between the two standards, it is considered that the control techniques, options and containment systems currently used for managing an incident involving fossil diesel would also be suitable for managing an incident involving synthetic diesel.

8.5.1.1 Behaviour of leaks and spills

As specified in Table 47, BS EN 15940 (European Standards, 2023) and BS EN 590 (British Standards Institution, 2024) indicate that synthetic diesel is less dense (0.77–0.79 kg/L at 15^{o}C) than fossil-based diesel certified under BS EN590 (0.820–0.835 kg/L). However, this difference in density is not expected to affect the way that synthetic diesel is treated compared to fossil diesel during an incident.

The lower density of synthetic diesel relative to water, combined with its composition as a paraffinic mixed hydrocarbon light oil, means it will collect and float on top of water bodies. This characteristic offers advantages for tertiary containment and recovery, as well as for the effectiveness of existing oil/water separator and interceptor technologies.

8.5.1.2 Behaviour in air

The relevant fuel standards do not specify the vapour density of fossil or synthetic diesel. However, hydrocarbons with a carbon chain length greater than two typically exhibit a vapour density > 1 relative to air. For example, propane (C_3) has a vapour density of 1.56 (Haz-Map, 2025).

Heavier-than-air vapours can accumulate in low-lying and below-ground areas, where they may persist and require a high degree of ventilation to ensure the area is safe. These vapours can travel some distance from the original source of a liquid leak or spill, with the potential to encounter an ignition source. Their persistence in confined spaces, such as drainage systems, presents a scenario where the flammable hazard may remain for extended periods. As a result, synthetic diesel vapour is expected to present the same low-lying and drainage-related flammability risks as fossil diesel.

The vapour pressure of a substance is an important factor in anticipating vapour generation from a liquid. From an incident management perspective, it also helps assess the potential for flammable atmospheres and fuel/air mixtures to form. Although the vapour pressure of synthetic diesel is not specified in BS EN 15940 and could not be found in the literature, flash point data can serve as a useful proxy for estimating its volatility relative to fossil diesel.

A lower flash point temperature indicates that less energy is required to produce sufficient vapour to form a potentially ignitable fuel/air mixture, suggesting greater volatility. BS EN 15940 specifies that the flash point of synthetic diesel (a paraffinic liquid produced via synthesis or hydrotreatment) must exceed 70°C. In comparison, the BS EN 590 standard for fossil diesel requires a minimum flash point of 56°C. Based on this difference, synthetic diesel is anticipated to be less volatile than fossil diesel.

This lower volatility is advantageous from a safety perspective, as it reduces the likelihood of flammable atmospheres developing.

8.5.1.3 Behaviour in water

While BS EN 15940 does not specify the water solubility of synthetic diesel, available literature indicates that the solubility of diesel in water is low, typically in the range of 0.2-0.5 mg/L (WHO, 1996). Given the similarities in chemical composition, it is reasonable to assume that the solubility of FT- and e-diesel in water is also likely to be low.

As discussed above, synthetic diesel is anticipated to float on water, meaning that secondary containment options used for fossil diesel, such as oil/water separators, will still be effective. Similarly, the recovery options used for fossil diesel on water bodies, such as over damming, skimmers, and floating booms/barriers, are viable options for tertiary containment and recovery.

8.5.1.4 Flammability

Leaks and spills of flammable liquids pose a fire hazard, and the flash point of flammable liquids is an important primary data point when assessing this hazard within incident management.

As the temperature of a liquid approaches its flash point, sufficient vapour can be produced to enable ignition. As Table 47 reported, the flash point for synthetic diesel is higher (>70°C) than that for fossil diesel (>56°C), suggesting that the associated flammability hazard may be lower for synthetic diesel.

Factors that may cause high flash point substances to ignite are:

- Aerosolised dispersal
- High temperature environment (ground temperature, bund temperature as opposed to air temperature, surface temperature of equipment, etc.)
- Contamination with more flammable substances
- Wicking on porous materials (absorbent material, clothing etc.)
- Increased pressure
- Increased levels of oxygen
- High energy ignition source

An additional metric for assessing the incident management challenges associated with synthetic diesel is the cetane number. Under normal operating conditions, BS EN 15940 specifies a minimum cetane number of >70 for synthetic diesel, compared to >51 for fossil diesel under BS EN 590 (see Table 47). This indicates that, during standard engine operation, synthetic diesel ignites more easily and more readily than fossil diesel, contributing to more efficient combustion.

However, in the context of a leak or spill, where compression and elevated pressures are unlikely, the flash point becomes the more relevant measure for assessing ignition risk. Given that synthetic diesel has a higher flash point than fossil diesel, it is considered less

ignitable in such scenarios. While it remains flammable, the increased flash point suggests a reduced ignition hazard in spill conditions.

Flammable and explosive limits data for synthetic diesel could not be identified in the available literature. Addressing this data gap would enable a more complete assessment of potential fire risks. In incident management contexts, flammable/explosive limits, flash points, vapour pressures, and vapour densities are typically considered together to evaluate the likelihood and severity of fire hazards.

The lower flammable or explosive limit is especially important in risk assessment. Below this concentration, the mixture is too lean to burn or explode. Substances with a low lower flammable limit pose a greater risk if that concentration is achievable, particularly in confined or enclosed spaces, where vapour accumulation is more likely. Such situations increase the risk of ignition and explosion.

Identifying and stopping the source of a leak should be a primary response action, alongside isolating the affected area and removing personnel who may be exposed to danger. A continual review of potential ignition sources is essential to maintaining a safe system of work. The use of monitoring and detection equipment to assess vapour concentrations and overall risk levels is also critical in managing incidents safely and effectively.

8.5.2 Physicochemical properties and behaviour in the environment of SAF

As discussed in Section 7.3, limited data on the specific properties of the SAF variants under consideration in this report was available in the literature at the time of writing. However, these SAFs must be produced using pathways approved under ASTM D7566 (ASTM, 2024), which provides a basis for comparison in incident assessment against fossil jet fuel, produced in accordance with ASTM D1655 (ASTM, 2022).

8.5.2.1 Behaviour of leaks and spills

The expected density range of SAF varies slightly depending on the production pathway. Pathways that include SPK, such as FT-SPK, FT-SKA and AtJ-SPK, are required to achieve densities in the range of 0.73 to 0.80 kg/L. In comparison, AtJ-SKA is required to fall within the range of 0.75 to 0.88 kg/L. These values are similar to those specified for conventional Jet A-1 under the ASTM 1655 fuel standard, which also requires a density between 0.75 and 0.88 kg/L. Therefore, existing incident management techniques used for conventional Jet A-1 fuel should also be suitable for these sustainable aviation fuels.

8.5.2.2 Behaviour in air

No data on the vapour density of SAF is available in the literature. However, SAF typically comprises C_8–C_{16} hydrocarbons (IEA Bioenergy, 2024d). As noted above in section 8.5.1.2, a liquid with this chemical composition is expected to exhibit a vapour density of >1 relative to air, i.e., to be heavier than air.

As discussed previously, the impact of vapour density on incident management is high, as vapours with high vapour densities will be low-lying, collecting along the ground and lower-than-ground areas, and may be persistent, requiring extended time periods or forced ventilation methods to clear areas.

As for synthetic diesel, flash point data (see Table 46) can be used as a proxy for incident management purposes. Fuels with a flash point above 38°C fall under the Globally Harmonised System classification as Category III flammable liquids (UNECE, 2023). Thus, despite having a flash point above ambient temperature, there remains a hazard and associated risk of ignition in the event of a loss of containment. ASTM D7566 (ASTM, 2024) stipulates that the flash point for the SAFs examined in this report must be >38°C, as with the fossil-based Jet A-1 produced according to ASTM D1655 (ASTM, 2022). Therefore, the SAFs considered in this report are expected to behave similarly to conventional fossil-derived Jet A-1 in incident scenarios.

8.5.2.3 Behaviour in water

Water solubility is not specified in ASTM D7566 (ASTM, 2024) or ASTM D1655 (ASTM, 2022); however, evidence from kerosene-type fuels indicates that SAF, like conventional Jet A-1, exhibits low water solubility, being a hydrocarbon-based paraffinic liquid.

The aromatic content of SAF varies by production pathway (see Table 46). For the SAFs considered, FT-SKA may contain up to 20 wt% aromatics, whereas FT-SPK and AtJ-SPK contain <0.5 wt%. For comparison, conventional Jet A-1, may contain up to 26.5 vol% aromatics. Aromatic hydrocarbons generally exhibit higher water solubility than paraffinic hydrocarbons. Therefore, because SAF generally contains substantially lower aromatic content than conventional Jet A-1, it is expected to have lower water solubility.

The expected low water solubility, combined with the fact that SAF is less dense than water, means that the fuel is anticipated to float, so secondary containment systems such as oil/water separators remain effective. On water bodies, recovery methods such as over damming, skimmers, floating booms and barriers remain viable options for tertiary containment and recovery, and equipment construction materials used in containment materials for fossil fuels are applicable for use with sustainable aviation fuels.

An octanol-water partition coefficient is currently only available for FT-SPK, which is reported as >6.5 (see Table 46). In comparison, safety data sheets for conventional Jet A-1 fuel give a value of 3.3 to 6. These values indicate that in both cases, the fuels favour mixing and dissolving with oils/lipids and exhibit a high degree of lipophilicity, meaning that there is the potential for bioaccumulation when introduced to biological organisms according to the Stockholm Convention for Persistent Organic Pollutants (UN Environmental Programme, 2023). However, a high degree of lipophilicity means that there is separation when in contact with water. Combined with the density of sustainable aviation fuel, the sustainable aviation fuel will float on top of water bodies or water within bunding/containment systems. The likelihood of contact with biological organisms needs to be established to provide an accurate assessment of the threat to organisms from bioaccumulation.

8.5.2.4 Flammability

As described in Table 46, the flash points of both SAF and fossil Jet A-1 must be greater than 38°C. This flash point indicates that there could be a fire risk, as the temperature can be reached relatively easily during an incident. However, this is a minimum requirement, and the actual flash point of SAF may be higher in practice.

If the temperature of any liquid leak or spill exceeds the flash point, then the introduction of an ignition source can lead to combustion. Factors that can cause flammable liquids with higher than ambient flash points to ignite do exist, and are applicable to all flammable liquids with such flash points. These factors include:

- Aerosolised dispersal
- High temperature environment (ground temperature, bund temperature as opposed to air temperature, surface temperature of equipment etc.)
- Contamination with a more flammable substance
- Wicking on porous materials (absorbent material, clothing etc.)
- Increased pressure
- Increased levels of oxygen
- High energy ignition source

The identification and removal of ignition sources is a priority consideration for the safety of personnel working within any area of a leak or spill of fuel. The availability of suitable extinguishing media is also required immediately upon confirmation of a leak or spill. Cordons to protect personnel should reflect the risk of ignition from unknown ignition sources, as well as identifying the potential for a cascading event where nearby hazards are triggered by fire or catch fire.

As for synthetic diesel, no data on the flammable and explosives limits of sustainable aviation fuel could be found in the literature. As Section 8.5.1.4 discussed, gathering data on these limits would allow further assessment of the potential fire risk posed by sustainable aviation fuels.

8.5.3 Incident management for synthetic liquid light oils

The review of the physicochemical properties of synthetic diesel and sustainable aviation fuel in Sections 8.5.1 and 8.5.2 showed the similarities in physical properties between these alternative fuels and the fossil fuels they were designed to replace. From an incident management perspective, this allows the protocols and processes used in managing the equivalent fossil fuel incidents to be utilised for these synthetic liquid light oils.

8.5.3.1 Spills and leaks

Spills of these synthetic oils are likely to be predominately in the liquid phase. Evaporation can occur, leading to the potential creation of a flammable atmosphere, but the potential for evaporation into the vapour phase may be lower for synthetic diesels, which are less volatile than sustainable aviation fuels.

The synthetic fuels also display low levels of solubility and are less dense than water, so initially they will remain predominately on the surface when released into water. These behaviours are equivalent to those displayed by their fossil fuel equivalents. Thus, the strategies used for fossil fuel spills and leaks are equally applicable to the synthetic oils.

8.5.3.1.1 Containment

Standard hydrocarbon fuel secondary containment options are also applicable for synthetic oils. These include the use of permanent bunding, transfer to alternative storage containment, and the construction of temporary bunds. Interceptors and oil/water separators can also be used in the same way as for a fossil fuel release.

Tertiary containment options for fossil fuel releases are also suitable for synthetic oils. For releases onto water, booms can be used to control the spread of contamination. For smaller spills on land, oil-absorbent materials remain an effective option.

Collection methods from secondary and tertiary containment can also follow the same approaches as those used for fossil fuels. The same pumping techniques can be applied during a comparable incident. Methods developed for collecting fossil fuels released to water or land, such as water skimmers, can also be deployed effectively for synthetic oil spills.

8.5.3.2 Release to controlled waters

The review of the physicochemical properties of synthetic diesel and sustainable aviation fuel in Sections 8.5.1 and 8.5.2 highlighted data gaps that limit the ability to fully predict the behaviour of synthetic oils when released to controlled waters. However, a consideration of their predicted chemical compositions supports the conclusion that, from an incident management perspective, they are expected to behave similarly to the equivalent fossil fuels. The key physicochemical properties influencing this include low water solubility, densities lower than water, and high octanol–water partition coefficients.

The primary behaviour following a release to controlled waters will be to float on the surface. The longer-term aquatic environmental risks are likely to be comparable to those from fossil fuel releases. As such, equivalent measures should be implemented to control and monitor long-term impacts. The monitoring techniques currently used for fossil fuel incidents in controlled waters will also be applicable to synthetic oils.

8.5.3.3 Fire

Fire and explosion control will be a major consideration in incident management for these synthetic oils. In fire conditions, synthetic oils will behave in the same way as the equivalent fossil-based oils, and the same processes and protocols can be utilised as for an equivalent incident fossil fuel.

8.6 Considerations for incident management from the storage of feedstocks

8.6.1 Solid biomass

From an incident management perspective, the major concern in the storage of biomass is fire risk. Chemical oxidation and microbial activity within stored biomass can lead to a self-heating reaction, with the possibility of temperatures reaching the ignition temperature of the biomass, causing self-combustion. Several factors, such as moisture content, ambient temperatures, oxygen levels and storage quantities, can influence the rate at which self-heating occurs. Storage sites therefore require effective fire detection and suppression systems.

Early fire detection is critical, but is challenging due to the insulating properties of biomass, which increase the challenge of detecting temperature increases within stored biomass. Changes in the temperature of stored biomass over time provide a strong indication that a self-heating reaction is occurring. Monitoring for increased levels of carbon monoxide and volatile hydrocarbon molecules in storage areas can also indicate when heating is occurring, as these compounds are generated by oxidation reactions.

Fire suppression options include the use of inert gases to deplete oxygen levels and stop the combustion process, as well as the use of water and foam. Consideration of the collection of fire water and foam is required.

Where biomass is present as a dust, there is also a risk of dust explosions. The transfer of biomass increases the potential of generating airborne dusts. When biomass containing dust is stored, it is necessary to consider risk reduction and control measures (Ennis, 2016).

Self-heating and explosion risks are also applicable to the transportation of biomass both on and off-site.

8.6.2 Renewable alcohols

Renewable alcohols (e.g. ethanol, butanol and isobutanol derived from sugar- or starch-based biomass feedstocks) are feedstocks for the alcohol to jet process described in Section 4.8. From an incident management perspective, renewable alcohols have physicochemical properties equivalent to alcohols derived from other manufacturing processes. Therefore, incident management plans for storage can follow the same approach, with the main areas of concern being fires and spills/leaks.

Short carbon chain alcohols are volatile liquids at ambient temperatures, with flash points leading to them being classified as flammable under the United Nations Globally Harmonised System for classification and the UK Carriage of Dangerous Goods Regulations. Where stored in sufficient concentrations, this brings them within the scope of

COMAH. Therefore, incident management planning should follow the requirements of these regulations.

Storage tanks should consider standard areas for tanks containing flammable liquids, with consideration given to containment, separation, ventilation, control of ignition sources and fire protection and precautions.

The extinguishing media for alcohols is typically alcohol-resistant foam, although a water spray can be used if this is not available.

With regard to spills and leaks, short chain carbon alcohols display a high level of solubility in water. Therefore, secondary and tertiary containment measures need to consider that the alcohols are present in the water phase. Water solubility presents an elevated risk level for aquatic environments in the event of an off-site release of the feedstock.

Further information on Best Available Techniques for the management of alcohols can be found in the Best Available Techniques Reference Document for the Production of Large Volume Organic Chemicals (European Commission, 2017).

8.7 Summary

The above discussion demonstrates that, in many cases, incident management strategies for the alternative fuels considered in this report are likely to align closely with those developed for fossil fuels.

For ammonia, biomethane and e-methane, this is because the chemical properties of these substances are identical to their fossil-derived equivalents. The supply chains for these materials are already well established in the chemical and fertiliser industries, and incident management practices have been developed, reviewed and refined over time to address risks and incorporate lessons learned from previous incidents (Highways England, 2019).

In the cases of synthetic diesel and SAF, the chemical composition and physicochemical properties of these fuels are designed to closely match those of the fossil-based fuels they replace. Consequently, their behaviours and appropriate responses during an incident are also likely to be equivalent.

However, the nascency of these fuels means there is limited information on their physicochemical properties related to their release to the environment. Ongoing research and monitoring are likely to be important to update incident management strategies as new information becomes available. Similarly, as these fuels become more widespread, real-world incident data and case studies will help to validate and refine response strategies.

9 Summary

Alternative fuels will play a crucial role in achieving the UK's target of reaching net-zero by 2050, particularly in the transport, heat and power, and industrial sectors (DESNZ, 2021a).

This study provides a detailed analysis of 10 alternative fuel production pathways, selected because they represent those that are more mature, i.e., have higher TRLs and consequently are more likely be deployed to meet the increased demand for alternative fuels in the UK by 2040.

As shown in Section 3.1, to date, the deployment of alternative fuels in the UK has mainly been in the transport sector, driven by the RTFO. Section 3.2 showed that this trend is likely to continue. Key policies such as the RTFO and the SAF mandate provide a clear trajectory for the deployment of alternative fuels in the transport sector, while the plants that have received funding from the AFF provide an indication of UK domestic SAF production in the near term, to 2030. Ammonia is also likely to be an important alternative transport fuel, particularly in the maritime sector. However, while this analysis shows that the demand for ammonia is likely to increase significantly, the maximum demand for ammonia is highly uncertain.

Aside from the transport sector, the analysis suggests that the demand for biomethane for domestic heat/power generation is also likely to increase significantly. However, the demand from other sectors such as industry and manufacturing is much less certain, with existing reports focusing mainly on the role of low carbon hydrogen.

Although there is a clear expectation that the demand for alternative fuels will increase significantly in the future, biomethane is the only fuel considered in this study that is currently produced commercially in the UK.

Section 4 provided a detailed overview of the production pathways and identified likely process configurations, operating conditions and potential emissions to land, air and water. In general, the production pathways covered in this study have not yet been deployed at significant commercial scale and range from TRL 5 to 8. Consequently, the availability of data was a limiting factor in this analysis.

A stakeholder workshop was held in an attempt to fill identified data gaps, such as operating conditions and typical concentrations of the identified pollutants that are generated. However, feedback from stakeholders directly involved in commercialising these processes suggested that this information is not currently known and/or is considered proprietary. Either way, it is unlikely to be publicly available.

The potential risks to human health that could arise from emissions of substances to the environment from the production of these fuels were discussed in Section 6. This was a hazard-based assessment, due to a general lack of information on the concentrations of these pollutants emitted, as identified in Section 4. Overall, the hazards of the main pollutants are well understood. However, more information is required to understand the

concentrations in which they are produced, to allow evaluation of the risk. This could form an area of future research.

Section 7 summarised the physicochemical properties of the alternative fuels in comparison to their fossil analogues. For ammonia and methane, the properties of the “alternative” fuels are identical to their fossil analogues. While it is not possible to specify the exact properties of SAF and synthetic diesel, relevant fuel standards provide a robust indication of the range of properties that can be expected from these fuels. In general, the properties differ slightly from their fossil equivalents, but not enough that significant changes in their behaviour would be expected.

The review of physicochemical properties was then used to assess the incident management requirements of the alternative fuels.

Ammonia has a unique set of physicochemical properties relative to both the other alternative fuels and existing fossil fuels. Therefore, current incident management strategies for fossil fuels will not be applicable to ammonia incidents. However, established incident management practices from the chemical industry, where ammonia is produced and stored in large quantities, are applicable to its use as a fuel.

Biomethane and e-methane properties are identical to those of the natural gas. The incident management techniques used for natural gas are therefore highly applicable to biomethane and e-methane.

The properties of the synthetic light liquid oils in the synthetic diesel and sustainable aviation groupings are sufficiently similar to those of fossil-derived diesel and aviation fuels. The incident management techniques used for these fossil fuels are therefore highly applicable to incidents with synthetic light liquid oils.

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11 Appendix

11.1 UK REACH

The UK regulation on the registration, evaluation, authorisation and restriction of chemicals (REACH) applies to the majority of chemical substances that are manufactured or imported to Great Britain and is summarised in Table 50. It covers chemical substances and mixtures thereof. On this basis, all of the alternative fuels covered in this report fall within the scope of this Regulation.

Table 50. Summary of Regulation (EC) No 1907/2006 concerning the Registration, Evaluation, Authorisation and Restriction of Chemicals (REACH)

Scope:	Applies to substances on their own, or in mixtures or articles, that are manufactured in or imported into Great Britain. Made up of four main elements: registration, evaluation, restriction and authorisation. UK REACH and EU REACH operate independently of each other. Under the Northern Ireland Protocol, EU REACH continues to apply in Northern Ireland. Transferred into GB law through the European Union (Withdrawal) Act 2018, UK REACH. View Online	
Responsible authority:	HSE	
Lifecycle scope:	Production	
Alternative fuels in scope:	✓ Ammonia ✓ e-methane ✓ Biomethane ✓ FT-SPK ✓ AtJ-SPK	✓ FT-SKA ✓ AtJ-SKA ✓ e-diesel ✓ HTL SAF/diesel ✓ Pyrolysis SAF/diesel

11.2 Industrial Emissions Directive (2010)

The Industrial Emissions Directive (2010) sets out rules aimed at the prevention and control of pollution arising from industrial activities, and is summarised in Table 51. This Directive applies to activities including:

- Gasification or liquefaction of other fuels with a total rated thermal input of 20MW or more
- Production of simple hydrocarbons (linear or cyclic, saturated or unsaturated, aliphatic or aromatic)
- Production of inorganic chemicals such as ammonia

Thus, production of all of the alternative fuels considered in this study is likely to fall under the scope of this Directive.

Table 51. Summary of Directive 2010/75/EU of the European Parliament and of the Council of 24 November 2010 on industrial emissions (integrated pollution prevention and control) (Recast)

Scope:	An integrated approach to controlling emissions to air, water and land from industrial facilities. Large industrial facilities must use Best Available Techniques (BAT) to reduce emissions. BAT reference documents outline the BAT conclusions and emission limits. Transferred into GB law through the European Union (Withdrawal) Act 2018. View online	
Responsible authority:	DEFRA, EA, NRW, SEPA, NIEA	
Lifecycle scope:	Production	
Alternative fuels in scope:	✓ Ammonia ✓ e-methane ✓ Biomethane ✓ FT-SPK ✓ AtJ-SPK	✓ FT-SKA ✓ AtJ-SKA ✓ e-diesel ✓ HTL SAF/diesel ✓ Pyrolysis SAF/diesel

11.3 Environmental Permitting Regulations 2016

The Environmental Permitting (England and Wales) Regulations 2016 implement the requirements of the Industrial Emissions Directive in England and Wales, and are summarised in Table 52. All of the alternative fuels considered in this study are likely to fall under the scope of this Directive.

These Regulations establish a framework for permitting activities that may impact human health or the environment, requiring operators to obtain a permit or register exemptions for "regulated facilities". While permits typically cover air emissions from industrial processes, additional requirements may apply for discharges to water (e.g. cooling water, process effluents) and waste management (e.g. by-products, sludges). These must be assessed on a case-by-case basis by the Environment Agency or Natural Resources Wales.

Table 52. Summary of Environmental Permitting (England and Wales) Regulations 2016

Scope:	Provides a consolidated framework for regulating activities that may harm human health or the environment. Requires operators of "regulated facilities" to obtain a permit or register certain activities as "exempt facilities". The permits set conditions for emissions control and may also include requirements for water discharges and waste management. View online	
Responsible authority:	EA, NRW	
Lifecycle scope:	Production, storage	
Alternative fuels in scope:	✓ Ammonia ✓ e-methane ✓ Biomethane ✓ FT-SPK ✓ AtJ-SPK	✓ FT-SKA ✓ AtJ-SKA ✓ e-diesel ✓ HTL SAF/diesel ✓ Pyrolysis SAF/diesel

11.4 Greenhouse Gas Emissions Trading Scheme Order 2020

The Greenhouse Gas Emissions Trading Scheme Order 2020 establishes the UK Emissions Trading Scheme, which is intended to support the UK to meet its GHG emissions reduction targets. This scheme is summarised in Table 53. Relevant to this study, the Greenhouse Gas Emissions Trading Scheme Order applies to "energy intensive industries". Specifically, this refers to the use of combustion plants with ≥20MW thermal input, as well as those producing ammonia, hydrogen (H_2) or synthesis gas by reforming or partial oxidation, with a production capacity exceeding 25 tonnes per day. Therefore, the production of all of the alternative fuels in the scope of this report could trigger a UK ETS obligation if these criteria are met.

Table 53. Summary of The Greenhouse Gas Emissions Trading Scheme Order 2020

Scope:	Aims to reduce greenhouse gas emissions by setting a cap on emissions by sector (Cap and Trade principle). Total emissions are capped and then companies can trade their emission allowances. Companies must monitor and report their emissions. View online	
Responsible authority:	EA, NIEA, SEPA, NRW	
Lifecycle scope:	Production	
Alternative fuels in scope:	✓ Ammonia ✓ e-methane ✓ Biomethane ✓ FT-SPK ✓ AtJ-SPK	✓ FT-SKA ✓ AtJ-SKA ✓ e-diesel ✓ HTL SAF/diesel ✓ Pyrolysis SAF/diesel

11.5 Health and Safety at Work Act 1974

The Health and Safety at Work Act 1974 (HASAWA 1974) is the primary piece of legislation covering occupational health and safety in Great Britain and is summarised in Table 54. It outlines the general duties employers have towards employees and members of the public. Broadly, the HASAWA 1974 will ensure that alternative fuel producers and suppliers manage chemical hazards and prevent industrial accidents. Although the HASAWA 1974 does not apply to fuels explicitly, it covers all employers in Great Britain, so all of the fuels covered in this report are in scope.

Table 54. Summary of Health and Safety at Work Act 1974

Scope:	Regulates and enforces workplace safety standards, including those for handling and storing alternative fuels. View online	
Responsible authority:	HSE	
Lifecycle scope:	Production, storage, transport	
Alternative fuels in scope:	✓ Ammonia ✓ e-methane ✓ Biomethane ✓ FT-SPK ✓ AtJ-SPK	✓ FT-SKA ✓ AtJ-SKA ✓ e-diesel ✓ HTL SAF/diesel ✓ Pyrolysis SAF/diesel

11.6 The Control of Major Accident Hazards Regulations 2015

The COMAH Regulations, summarised in Table 55, aim to prevent and mitigate the effects of major accidents involving dangerous substances which can cause serious damage/harm to people and/or the environment. The COMAH Regulations apply to "establishments", which are defined as locations under the control of an operator where a dangerous substance is present in quantities equal to or in excess of those specified in Schedule 1 of the COMAH Regulations.

These thresholds vary depending on the hazard classification of the substance (e.g. flammability, toxicity, environmental hazard) and whether it is specifically named in the schedule. For example, flammable gases and liquids have different lower-tier and upper-tier thresholds depending on their properties, with the most hazardous flammable substances triggering COMAH at quantities as low as 10 tonnes. Therefore, some of the alternative fuels considered in this study – particularly those that are flammable or toxic – may fall within scope of the COMAH Regulations, depending on their classification and the quantities held on site.

Thus, all of the alternative fuels considered in this study are covered by the COMAH Regulations.

Table 55. Summary of The Control of Major Accident Hazards Regulations

Scope:	Aims to prevent major accidents resulting from the storage or handling of hazardous chemicals. Has two levels: lower (operators must prepare a Major Accident Prevention Policy (MAPP) outlining measures to prevent accidents) and upper (requires MAPP, a detailed safety report and an internal emergency plan) tiers, based on the status of the establishment. Related to EU Seveso II Directive. View online	
Responsible authority:	HSE, EA, ONR	
Lifecycle scope:	Any point in lifecycle where threshold quantities are exceeded (excluding transport)	
Alternative fuels in scope:	✓ Ammonia ✓ e-methane ✓ Biomethane ✓ FT-SPK ✓ AtJ-SPK	✓ FT-SKA ✓ AtJ-SKA ✓ e-diesel ✓ HTL SAF/diesel ✓ Pyrolysis SAF/diesel

Table 56 presents the likely classification under the COMAH regulations of the finished fuels and relevant feedstocks, and the associated thresholds for the two levels.

Table 56. COMAH classification for identified key substances in the alternative fuel production pathways.

Type	Substance	Alternative fuel production routes	Relevant section of Schedule 1 of COMAH	Lower tier thresh-hold (t)	Upper tier thresh-hold (t)
Fuel	Methane[27]	Biomethane e-methane	Part 1: P2 Flammable gases, Category 1 or 2	10	50
Fuel	Kerosene	FT-SPK FT-SKA AtJ-SPK AtJ-SKA HTL Pyrolysis	Part 2: 34. Petroleum products and alternative fuels	2,500	25,000
Fuel	Diesel	e-diesel HTL Pyrolysis			
Fuel	Ammonia	Ammonia	Part 2: 35. Anhydrous ammonia	50	200
Feed-stock	Ethanol[28]	AtJ-SPK AtJ-SKA	Part 1: P5b Flammable liquids Category 2 or 3 where particular processing conditions, such as high pressure or high temperature, may create major-accident hazards, or other liquids with a flash point ≤ 60°C where particular processing conditions, such as high pressure or high temperature, may create major accident hazards.	50	200
Feeds tock	Hydrogen	e-methane Pyrolysis	Part 2 15. Hydrogen	5	50

[27] If biomethane from gasification and for gasification were to be considered a natural gas substitute in a similar way to biomethane (upgraded biogas), then the relevant part of the schedule would be Part 2: 18. Liquefied flammable gases, Category 1 or 2 (including LPG) and natural gas, where the thresholds for lower and upper tiers are 50 tonnes and 200 tonnes respectively.

[28] Pressure and temperature ranges during the Alcohol-to-Jet production process are likely to be sufficiently high to potentially create major-accident hazards.

Type	Substance	Alternative fuel production routes	Relevant section of Schedule 1 of COMAH	Lower tier thresh-hold (t)	Upper tier thresh-hold (t)
		HTL Ammonia			

11.7 Control of Pollution (Oil Storage) (England) Regulations 2001

The Control of Pollution (Oil Storage) (England) Regulations 2001, summarised in

Table 57, set the legal requirements for the storage of oil in England. These Regulations require a person having custody or control of oil to carry out certain works and take certain precautions and other steps for preventing pollution of any waters which are controlled waters for the purposes of Part III of the Water Resources Act 1991. The Regulations state that *"oil" means any kind of oil and includes petrol*. Based on this definition, ammonia and e-/biomethane are out of scope of these Regulations. Ricardo's interpretation is that the distillate type fuels (see Section 4 for details) are covered by these Regulations. While no specific changes to the Regulations are currently proposed, there is potential for future policy development to expand or adapt oil storage controls to address the growing use of alternative fuels and associated pollution risks.

Table 57. Control of Pollution (Oil Storage) (England) Regulations 2001

Scope:	Aims to prevent water pollution from oil storage facilities in England. Applies to anyone who has custody or control of oil stored in above ground containers >200 litres. View online	
Responsible authority:	EA	
Lifecycle scope:	Storage	
Alternative fuels in scope:	× Ammonia × e-methane × Biomethane ✓ FT-SPK ✓ AtJ-SPK	✓ FT-SKA ✓ AtJ-SKA ✓ e-diesel ✓ HTL SAF/diesel ✓ Pyrolysis SAF/diesel

11.8 The Petroleum (Consolidation) Regulations 2014

The Petroleum (Consolidation) Regulations 2014, summarised in

Table 58, consolidate and modernise the petrol storage legislative framework in England, Scotland and Wales. These Regulations define petrol as petroleum or a mixture of petroleum and one or more substances which:

- Is liquid or viscous at a temperature of 15°C and a pressure of 101.3 kPa
- Has a flashpoint less than 21°C

The Petroleum (Consolidation) Regulations 2014 apply specifically to petroleum spirit, defined as liquids with a flash point below 21°C used in internal combustion. Therefore, based on the physicochemical properties of the alternative fuels identified in Section 4, none of the fuels covered in this study are within the scope of these Regulations. While there are currently no proposals to expand the scope, future updates may be considered to address storage risks associated with emerging low-carbon fuels.

Table 58. Summary of The Petroleum (Consolidation) Regulations 2014

Scope:	Aims to consolidate the legislative framework for petroleum storage in England, Scotland and Wales. Covers general prohibitions on keeping petrol without proper certification, storage certification conditions, storage conditions, enforcement and transitional provisions. View online	
Responsible authority:	HSE	
Lifecycle scope:	Storage	
Alternative fuels in scope:	× Ammonia × e-methane × Biomethane × FT-SPK × AtJ-SPK	× FT-SKA × AtJ-SKA × e-diesel × HTL SAF/diesel × Pyrolysis SAF/diesel

11.9 The Alternative Fuel Labelling and Greenhouse Gas Emissions Regulations 2019

The Alternative Fuel Labelling and Greenhouse Gas Emissions Regulations 2019, summarised in Table 59, implement a common set of labels and identifiers for alternative fuels in the UK. Within these Regulations, “alternative fuel” includes:

- Liquid or gaseous biofuels derived from biomass
- Synthetic and paraffinic fuels
- Natural gas, including biomethane in gaseous (compressed natural gas) or liquefied form

On this basis, of the fuels covered in this report, only ammonia is not covered by these Regulations.

Table 59. Summary of The Alternative Fuel Labelling and Greenhouse Gas Emissions (Miscellaneous Amendments) Regulations 2019

Scope:	Aims to provide clarity and accessibility of alternative fuels for consumers by setting out certain labelling requirements for refuelling points with petrol-type, diesel-type and gaseous-type fuel dispensers, and motor vehicles as defined in section 185(1) of the Road Traffic Act 1988(a), the manufacture of which is completed on or after 1 April 2020. View online	
Responsible authority:	DfT	
Lifecycle scope:	Storage	
Alternative fuels in scope:	× Ammonia ✓ e-methane ✓ Biomethane ✓ FT-SPK ✓ AtJ-SPK	✓ FT-SKA ✓ AtJ-SKA ✓ e-diesel ✓ HTL SAF/diesel ✓ Pyrolysis SAF/diesel

11.10 The Alternative Fuels Infrastructure Regulations 2017

The Alternative Fuels Infrastructure Regulations 2017 (SI 2017/897) implement the requirements of Directive (2014/94/EU) of the European Parliament and of the Council of 22nd October 2014, establishing a common framework of measures for the deployment of alternative fuels infrastructure in the UK. These Regulations are summarised in Table 60. These Regulations pertain to the deployment of electric vehicle charge points, hydrogen refuelling infrastructure and shore-side electricity for seagoing ships. Therefore, the fuels considered in this study are not in scope of these Regulations.

It is worth noting that Directive (2014/94/EU) of the European Parliament and of the Council of 22nd October 2014 includes provisions for the deployment of infrastructure for compressed and liquified natural gas, which is relevant for e-methane and biomethane. However, these requirements were not transposed into The Alternative Fuels Infrastructure Regulations 2017 (SI 2017/897).

Table 60. Summary of The Alternative Fuels Infrastructure Regulations 2017

Scope:	Aims to support the increased uptake of alternative fuels by vehicles or ships by ensuring accessible alternative fuel infrastructure in the form of electric vehicle charge points and hydrogen vehicle refuelling points. View online	
Responsible authority:	The Office for Product Safety and Standards	
Lifecycle scope:	Other	
Alternative fuels in scope:	× Ammonia × e-methane × Biomethane × FT-SPK × AtJ-SPK	× FT-SKA × AtJ-SKA × e-diesel × HTL SAF/diesel × Pyrolysis SAF/diesel

11.11 The Carriage of Dangerous Goods and Use of Transportable Pressure Equipment Regulations 2009

The Carriage of Dangerous Goods and Use of Transportable Pressure Equipment Regulations 2009 (CDG 2009) SI 2009/1348, summarised in Table 61, impose requirements and prohibitions in relation to the carriage of dangerous goods by road and by rail. These regulations apply to all of the alternative fuels covered in this study, as they meet the classification of dangerous goods by the European Agreement concerning International Carriage of Dangerous Good by Road (see Section 8 for details).

Table 61. Summary of The Carriage of Dangerous Goods and Use of Transportable Pressure Equipment Regulations 2009

Scope:	Regulates the carriage of dangerous goods by road and rail in Great Britain. The Directive provides for the safe and secure transport of dangerous goods such as hazardous chemicals, gases, petrol and diesel, and flammable products. View online	
Responsible authority:	DfT	
Lifecycle scope:	Other	
Alternative fuels in scope:	✓ Ammonia ✓ e-methane ✓ Biomethane ✓ FT-SPK ✓ AtJ-SPK	✓ FT-SKA ✓ AtJ-SKA ✓ e-diesel ✓ HTL SAF/diesel ✓ Pyrolysis SAF/diesel

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