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OPPORTUNITIES FOR PROVISION OF SYNTHETIC FUELS IN NORTHERN IRELAND FROM WASTE AND RE-USE OF CARBON

A Report by the Bryden Centre and CASE, Queen's University Belfast and Cenex
grant funded by the Department for the Economy, Northern Ireland

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1. EXECUTIVE SUMMARY

As the world transitions away from fossil fuels and reduces greenhouse gas emissions, key technologies such as electrification are predicted to displace much of the current fossil fuel use in transport, heating, and industry. However, during the energy transition and long after, there will remain a demand for fuels, albeit decarbonised, for applications in hard-to-abate sectors such as long-haul aviation, some industrial processes, and shipping. The reasons for this are manifold but are primarily due to the practical limitations of energy storage where, for example, advanced battery pack technology can provide only a fraction of the energy for a given volume relative to the same volume of a chemical energy carrier such as diesel. Therefore, even when accounting for differences in energy conversion efficiency, fuels remain highly attractive. Outside of the specific requirements for hard-to-abate sectors, there are also other applications where fossil fuel equivalents are desirable. Examples include bulk energy transport, infrastructure compatibility, long-term storage requirements or when capital/operating costs make alternatives impractical or uneconomic.

For the purposes of this report, fuels are essentially classified as energy storage materials which at some point undergo a direct or indirect chemical reaction with oxygen in the air to release energy in the form of heat and/or electricity. As such, there is a wide range of fuel types with the simplest being hydrogen, which, when reacted with oxygen (in the air) produces water. Pure hydrogen storage is difficult, and biological systems have evolved to store hydrogen in combination with other elements such as carbon, nitrogen, and sulfur in the form of liquid or solid compounds, which have much higher energy densities (energy per unit mass or volume). Fossil fuels result when these biogenic materials have been produced, converted, and stored over geological timescales and biofuels when the same or similar materials are produced over a much shorter time. Synthetic fuels (synfuels) result when such materials (either fossil or biological) are initially broken down into a set of gaseous molecular building blocks and then rebuilt back into a larger product. E-fuels are a final alternative which utilise building blocks generated using electrical energy, e.g., electrolysis to form hydrogen.

Northern Ireland has substantial opportunities to develop a non-fossil synthetic and/or e-fuels industry which could complement existing biofuels production for regional use or potential export. For example, there are a number of anaerobic digestion (AD) installations across NI which are principally producing biogas (biomethane and CO_2 mix) for use in combine heat power (CHP) systems and, in some cases supplying biomethane for heavy goods vehicles (HGVs). These AD plants will shortly be able to inject biomethane into the gas grid to supply domestic and industrial consumers, and recent analysis shows that NI has sufficient agricultural resources to be able to supply >75% of the domestic gas requirements (at present levels of consumption). This is before energy recovery from solid digestate is considered for upgrading to synfuels or where the biogenic CO_2 component of biogas is upgraded with green hydrogen to produce e-methane.

It is recognised that the market for bio/e-methane is basically that of a drop-in replacement for fossil gas which can be potentially produced at significant volumes within NI due to the scale of the agri-tech industry. At the same time, it is recognised that hydrogen and electrification have the ability to both reduce and displace bio/e-methane from the NI grid over the longer term and that this displacement would be accelerated by the differential pricing, which is expected to result from demand in the aforementioned hard to abate sectors. As such, the higher value of heavier synthetic fuels needed in aviation, for example, is likely to redirect biogenic carbon to such sectors and has been recognised by the UK committee on climate change, which reported that biogenic resources will be devoted to the production of synthetic aviation fuel (SAF) by 2040[1] .

A similar picture also applies to other biogenic fuels such as biomethanol, bio-DME, biodiesel and hydrotreated vegetable oil (HVO). Each of these can be derived from bio-feedstocks of varying origin. Biomethanol is also known as wood alcohol, bio-DME is a dehydrated version of that, and biodiesel and HVO are produced from waste vegetable oils or tallow. The availability of these feedstocks is, therefore, a limiting factor, and difficulties arise when energy competes with traditional markets, as exemplified by the debate on grass silage being used for supplementing AD production rather than for feeding livestock.

1 https://www.theccc.org.uk/publication/sixth-carbon-budget/

Ultimately, the supply of bio-derived feedstocks is expected to constrain the bioenergy sector, and as a result, several future pathways envisage a technology mix which employs renewable electricity to produce green hydrogen, which is then combined with CO_2 to produce e-fuels – e-methane, e-methanol, and e-diesel or hydrogen and non-carbon carriers such as ammonia, or used to boost the energy value of biological or carbon-rich wastes which are generally hydrogen deficient.

As part of this report, Cenex, who were established in 2005 as the UK's first Centre of Excellence for Low Carbon and Fuel Cell technologies, were commissioned to assess the opportunities for synthetic fuels from Agri-waste to support the Northern Ireland transport sector.
The key outcomes of this work are reported below.

1.1 Fuel and Transport Pathways

Cenex reviewed fuel and vehicle technology roadmaps in the on-road, off-road, aviation, rail and marine sectors to understand potential opportunities for Agri-fuel waste. Initial findings on the opportunity within NI and fuel type are as follows

Sector	Relative Opportunity	Potential Agri-fuel Type
Road Transport	Low	Renewable diesel, e-Diesel, Bio-methane
Rail	Low	Renewable diesel, e-Diesel
Agriculture, Mining & Construction	Moderate	Renewable diesel, e-Diesel
Marine	High	Renewable diesel, ammonia, bio-methanol, e-diesel
Aviation	High	Sustainable Aviation Fuel (SAF)

- The Marine and Aviation sector are likely to have a high future demand for fuels derived from Agri-fuel waste, such as renewable diesel, e-diesel, ammonia, methanol and SAF.
- There is a moderate opportunity to provide fuels to Agriculture, Mining and Construction where the roadmaps indicate renewable and e-diesel fuels may play a strong role in the future fuel mix.
- There is relatively limited opportunity in the short term for road transport until zero emission (ZE) fuels begin to dominate the sector from 2035.
- It is unlikely that there is sufficient time to fully adopt multiple fuel supply infrastructure before 2050; therefore, in the short term, 'drop-in' fuels should be supported that use existing infrastructure whilst market capability, and infrastructure is being developed for key markets in Marine and Aviation industries.
- Any investment in new infrastructure for transition fuels should be compatible with final 2050 future fuels such as SAF, Ammonia, and Synthetic diesel.
- The sustainability criteria of fuels are expected to become increasingly more stringent. Carbon Capture, Use and Storage (CCUS) should be considered for all new fuel production plants.

1.1.1 Exploitation Potential

- Cenex attempted to estimate the number of vehicles in NI. Of the data available, most vehicles in NI are road vehicles, with 81% of the market being cars, 10% vans and 2% trucks. Agriculture, Mining and Quarrying vehicles account for a few percent of the vehicle stock. The number of Aviation and Marine vehicles are unknown.
- UK industry fuel supply data were adjusted to estimate NI fuel demand. This showed that the current annual potential total market for waste Agri-fuels in the NI transport sector is estimated at 15,500 GWh with a market value of around £1bln. Key transport market sectors are Aviation (46%), Road Transport (25%) and Maritime (10%).
- The total market size was estimated to be similar by 2050. However, with the shift to ZE drive-trains and improvements in transport efficiency, the key markets in 2050 are estimated to be Aviation (58%), Maritime (16%) and Construction (12%).

1.1.2 Supporting Policy & Legislation

- Cenex undertook a high-level review of policy and legislation that could impact the use of Agri-fuels in transport options.
- Policy and legislation were separated into those driving the **Supply Side** (fuel suppliers) for renewable fuels and those driving the **Demand Side** (transport operators).
- Key fuel **Supply Side** policies include the ban on the internal combustion engine (ICE) in road transport, which will reduce the demand for liquid and gaseous fuels. The Renewable Transport Fuel Obligation (RTFO), which sets a target for fuel supply to have an increasing amount of renewable content, and the expected SAF Mandate, which would legislate an increase in the renewable content of aviation fuel.
- No strong policy legislation is yet in place for the decarbonisation of Marine, Agriculture, Mining and Construction Sectors.
- Key **Demand Side** (transport operator) policies legislate the monitoring of energy and emissions by large organisations but do not require emission reduction actions to be taken by transport operators.
- It was noted that the Republic of Ireland had announced plans to increase the renewable content of motor fuels and develop a CNG refuelling network. These present a market opportunity for NI Agri-fuels.

1.1.3 Future Economics of Renewable Fuels

- A study undertaken by E4Tech and Cenex in 2020 looked at the future economics of alternative fuel supplies for the off-road equipment sector.
- The study compared fuels on a total cost of ownership basis, which included fuel supply and use costs for an operator. The study considered fuels on a NOAK (nth of a kind) basis, which assumes costs of a mass market and mature fuel supply system.
- The study highlighted that bio-methanol, bio-LPG, e-methanol, ammonia, FAME, synthetic CNG and LNG could all potentially be cost competitive against the current cost of diesel fuel supply.

1.1.4 Comparison of Agri-fuel Demand

- A RAG matrix was used to summarise the potential performance in the 2035 and 2050 timeframe of the key renewable fuels.
- In the period to 2035, there is likely to be demand for drop-in diesel replacement fuels across Agriculture, Mining, Maritime, Construction and Road transport as these sectors look to decarbonise but awaiting maturity of 2050 net-zero fuel options. Demand for bio-methane would be limited by the availability of suitable ICE vehicles. There will be growing demand for SAF due to a mandate for increased use of the fuel, which is expected to be announced by the UK government over the next year.
- In the period of 2035 to 2050, there is likely to be a significant decline in demand from the Road transport sector, and also a decline from Agriculture, Mining and Construction sectors as these sectors are able to turn to ZE options. There is a strong demand from Maritime and the Aviation sector where long-distance transportation requires the energy density from liquid fuels. The RTFO legislation ceases in 2032 and is likely to refocus incentives for renewable fuels at hard to electrify areas such as heavy industry and long-haul shipping and aviation.

1.2 KEY RECOMMENDATIONS

This study presents a high-level prefeasibility assessment of opportunities for biogenic based and other synthetic fuels with the focus on how best to meet Northern Ireland's requirements. Fundamental to the use of NI's resources is a determination of the short, medium and long-term allocations to many competing end uses with the goal of NI becoming as close to self-sufficiency as possible by 2050. This will require shifting policy support to encourage market choices as technology options and supply chains mature in the coming decades.

1. Green hydrogen is an enabler for many synthetic fuels and investment is needed in production, storage, and distribution even if battery technology overtakes hydrogen for most vehicles.

2. Biogenic sources of carbon in NI are not sufficient to replace current fossil fuel use so additional feedstocks beyond hydrogen need to be considered. A pilot scale investigation of circular economy approaches where CO_2 is captured and used as a synfuel feedstock is desirable to establish the economics and co-benefits of this method.

3. Replacement of kerosene for home heating in off-grid locations is possible via boiler replacement and use of renewable DME or LPG – this option warrants further investigation to establish the economic feasibility.

4. A clear roadmap is needed to displace liquid and gaseous fossil fuels for heating and transport as well as to provide the energy input into e-fuels. This includes building out renewable electricity generation capacity as well as constructing the facilities and infrastructure for synthetic fuel production and distribution. The lifetime of large capital plant coupled with planning and construction timescales will mean that synfuel investments starting development today may well be in operation in 2050 – potentially locking in fuel choices and tying up local resources.

5. A specific feasibility study should be undertaken to look at the short to medium term opportunity for drop-in fuel supply to assist in the decarbonisation of existing transport segments, and the longer-term opportunity for supply of future fuels focused on the aviation and marine industries. The study should include potential scenarios for NI, including fuel supply, infrastructure, demand, environmental and economic opportunity.

6. Establish plan to maximise collection and utilisation of biogenic feedstock. These should include undertaking studies to determine collection/processing efficiency based on location of resources and to optimise apportionment to different requirements: energy (fuels), maintaining soil carbon, peat substitute/other agricultural/horticultural uses etc.

7. Review opportunities to increase biogenic feedstock production by 2030 such as encouraging aquaculture in NI marine areas.

8. The authors identified several areas during the study where further research needs to be conducted to increase the accuracy of reported values before investment decisions, and policy decisions should be made.

    a. Estimates of fuel use in NI should be peer-reviewed and refined with other more specific NI data sources and factors, where available, incorporated into the assumptions.

    b. The average annual GDP change in NI of approximately 1.8% per year (based on figures from the twenty years covering 1999 to 2019) has been applied to the market data. Further work is required to determine a more specific value considering wider factors such as transport mode shift, long-term impacts of recent events such as the war in Ukraine, Covid-19, Brexit, and Net-Zero.

    c. There was little or no data available on the number and types of vehicles in the NI construction, mining, aviation and marine sectors. Further research and industry consultation should be undertaken to determine the make-up of these vehicle parts in NI.


POWER PLANT

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3 LIST OF ABBREVIATIONS

AD	Anaerobic Digestion
AFLU	Agriculture, Forestry or Land Use (AFLU)
APR	Aqueous Phase Reforming
AQ	Air Quality
bbl	Barrel (of oil)
BECCS	BioEnergy Carbon Capture and Storage
BECCUS	BioEnergy Carbon Capture, Utilisation and Storage
BEV	Battery Electric Vehicle
CC	Carbon Capture
CCC	Climate Change Committee
CCGT	Combined Cycle Gas Turbine
CCS	Carbon Capture and Storage
CCUS	Carbon Capture Utilisation and Storage
CHP	Combined Heat and Power
CNG	Compressed Natural Gas
CO_2	Carbon dioxide
CO_2e	Carbon dioxide equivalents
COP	Coefficient of Performance
DACCS	Direct Air Carbon Capture
DAERA	Department of Agriculture, Environment and Rural Affairs
DfE	Department for the Economy
DME	Dimethyl Ether
ESOS	Energy Savings Opportunity Scheme
ETS	European Trading Scheme
EU	European Union
FAME	Fatty Acid Methyl Ester
FT	Fischer-Tropsch
GHG	Greenhouse Gas
GW	Giga Watt
GWh	Giga Watt Hour
HGV	Heavy Goods Vehicle
ICE	Internal Combustion Engine
IGCC	Integrated Gasification Combined Cycle
kt	Kilo Tonne
kt CO_2	Kilo tonnes CO_2
ktoe	Kilo tonne oil equivalent (to convert to GWh multiply by 11.83)
LCOE	Levelized Cost Of Energy
LPG	Liquid Propane Gas
MFO	Marine Fuel Oil

Mt CO_2	Mega tonnes CO_2
NI	Northern Ireland
NPP	Net Primary Productivity
rCNG	Renewable Compressed Natural Gas
RDF	Refuse Derived Fuels
rDME	Renewable Dimethyl Ether
RHI	Renewable Heat Incentive
rLPG	Renewable Liquid Propane Gas
ROCs	Renewables Obligation Certificates
RTFC	Renewable Transport Fuel Certificates
RTFO	Renewable Transport Fuel Obligation
SAF	Synthetic Aviation Fuel
tCO_2	Tonnes CO_2
ZE	Zero Emission

AD
AFLU
APR
AQ
bbl
BECCS
BECCUS

4. INTRODUCTION

KEY POINTS

- This section introduces some of the core principles needed to evaluate the production of synfuels in Northern Ireland.
- There are numerous fuel options available, ranging from pure hydrogen to more direct drop-in replacements such as jet fuel. In each case, the production of the fuel requires an energy source which is either derived from the feedstock used in the production or added as an external input to the system.
- In the case where the energy is derived from the feedstock, the resulting fuel products will have lower energy (due to system losses) but a higher fuel quality allowing them to be used as drop-in replacements.
- Additional energy inputs can include electricity (electrolysis), thermal (heat) or photochemical (using solar radiation). How these are sourced and used within the overall process will determine the net storage efficiency and carbon intensity of the final fuel.
- Demand for fuels in Northern Ireland is significant. It was estimated that over 2479kt of petroleum products per annum were consumed in Northern Ireland in 2019. Using this as a baseline and using green hydrogen and captured CO_2 as the feedstock, it was further estimated that approximately 16 GW of offshore wind would be required.
- Efficiency savings, system integration and utilisation of other energy carriers, including agri-wastes, will significantly lower this energy requirement, reduce energy losses as well as support a circular economy within Northern Ireland.

Achieving the ambitions of the recent Northern Ireland (NI) climate change act and DfE's Energy Strategy will help the UK meet its commitment to achieving net zero carbon emissions by 2050. A central part of reducing carbon emissions will be the transition away from fossil fuels via electrification and the use of low carbon footprint synthetic fuels for applications that cannot be electrified. To investigate the potential for synthetic fuels produced from waste and the re-use of carbon captured from industrial processes or other sources, and the impact this may have on the NI economy, a report was commissioned, and grant funded by the Department for the Economy (DfE) in NI. The Bryden Centre and CASE at Queen's University Belfast, in partnership with Cenex (the leading UK consultancy on renewable transport), were asked to evaluate the opportunities with a focus on utilising the potential biogenic and carbon resources of the region to produce fuels whilst also being cognisant of the existing infrastructure and wider industrial sectors.

For the purposes of this report, we will use the term synthetic fuel to refer to fuels produced by a number of routes, including:

1. Synthetic routes which use building blocks (e.g., carbon dioxide (CO_2), carbon monoxide (CO) and hydrogen (H_2)) derived from biological and not fossil feedstocks

2. E-fuels which are produced from the same building blocks but where these are produced using electrolysis (e.g., hydrogen from water or carbon monoxide from carbon dioxide)

3. Combinations of the above, including the use of green hydrogen to enhance or upgrade biological feedstocks to fuels. This would include, for example, hydrotreated vegetable oils (HVO), where the hydrogen was produced from electrolysis or biomass gasification.

Where relevant, we will refer to synthetic and e-fuels separately, where the former refers to the first category above, and the latter refers to the second in the above list. Each of these is distinct from biofuels which are produced from biological feedstocks, including, for example, biomethane, bioethanol and biodiesel.

4.1 The broad NI energy landscape

It has been reported that the total final energy consumption in Northern Ireland in 2019 was 52,476 GWh, of which power represented 14%, transport 30% and heat 56%[2] . Of this total, the energy associated with petroleum products was 28,833 GWh which was a reduction of 6,147 GWh when compared to the 2005 figures. While petroleum products vary in terms of their energy density, an average value of 47 GJ per tonne can be estimated from the DECC greenhouse gas conversion factors[3] and subsequently used to estimate the associated NI consumption as approximately 2.2 million tonnes (2208 kt), increasing to 2479 kt oil equivalent (ktoe) when using 41.88 GJ per tonne as the conversion factor.

Direct drop-in replacements to match the 2019 demand would therefore need to provide an equivalent energy output (assuming no efficiency improvements or growth), and here it can be calculated that to produce the same 28,833 GWh via wind energy at a reasonable capacity factor of 35% approximately 9.4 GW of installed turbines would be needed which is more than 7.5 times the total installed capacity of wind within NI in 2019 (1,250 MW[4]).

BEIS published projections in December 2021 for primary energy demand for the UK as part of their work on establishing a net-zero baseline[5]. These figures are converted for NI in Figure 1 below. Here, in the baseline case, we can see that the expectation is for significant fossil fuel use out to 2040+ *based on the assumption of UK government policies in place as of 2019 with* ***no further action.***

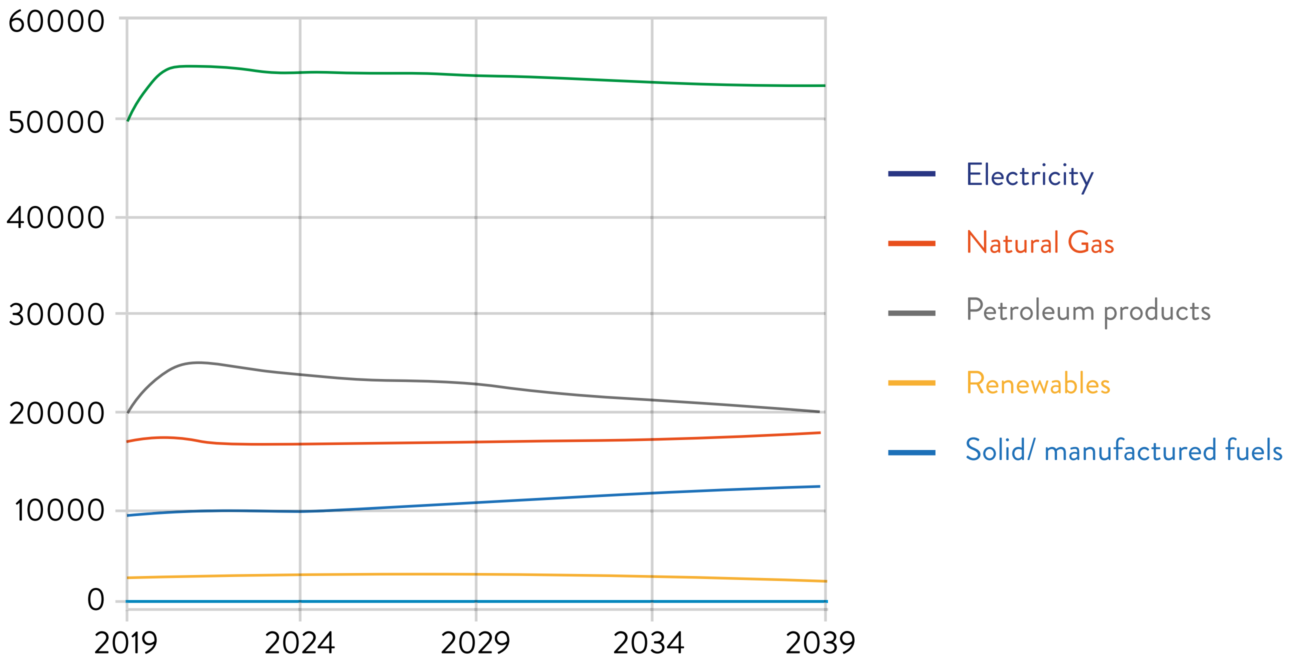


Figure 1 Estimated total final energy consumption for NI based on UK projections

If no additional actions were taken then the net impact on carbon emissions would be minimal. However, this is not a likely scenario. Here in NI we are impacted by both UK and NI Government policies and have unique challenges and resources which will make our approach and roadmap to net-zero significantly different to other parts of the UK.

[2] *Energy in Northern Ireland 2022, DfE*
[3] *https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/47732/7309-cca-draft-technical-guidance-app-b.xls*
[4] *Eirgrid All-Island Generation Capacity Statement 2019-2028*
[5] *Energy and emissions projections: Net Zero Strategy baseline (December 2021)*

[6] *https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/1038935/Annex-F-final-energy-demand_-_NZS_Baseline_.ods conversion based on 42 GJ per toe and 3.5% energy attributed to NI.*

4.1.1 Hydrogen as a replacement fuel

Green hydrogen is often promoted as a candidate to displace fossil fuels. If this approach were to be adopted in NI then the scale of the challenge needs to be assessed. Assuming that the energy required to produce hydrogen is 55 kWh/kg and using an energy density of hydrogen of 120 MJ/kg (lower heating value or LHV), the required regional wind capacity in NI to satisfy 2019 demand would be 15.5 GW producing approximately 865 kt of hydrogen per annum. It is clear that the use of hydrogen clearly requires a significant increase in installed renewables due to the efficiency losses in terms of conversion (≈71% efficient) and the use of the lower rather than higher heating value. Here the difference between the higher and lower heading value for hydrogen is 20 MJ/kg and represents the difference in energy which can result when the energy in produced steam is condensed and can be recovered and is one of the main reasons why condensing boilers have higher efficiency. If the higher heating value is realisable, then the installed renewables could reduce to 13.2 GW. Transport and storage losses and energy requirements would have to be evaluated for a full picture but are assumed for simplicity to be comparable to those for fossil fuels – this is unrealistic as is shown later.

While this value appears excessive, it is noted that large-scale projects for green hydrogen are being developed at present. For example, the NEOM Green Hydrogen Project in Saudi Arabia is planned as the world's largest utility-scale plant operating on 4 GW of associated renewable solar and wind energy. Using the same analysis as above, the 4GW of installed renewables with a reduced capacity factor of 29.5%[7] (due to location) and the same energy requirement per kg of hydrogen would yield an estimated 515 tonne/day of hydrogen (assuming 365-day operation) which is lower than the reported value of 650 tonne per day. It is noted that increasing the capacity factor to 37% would yield the equivalent output, thereby showing the sensitivity of the overall production capacities to this value. The NEOM project will use 120 Thyssenkrupp AG electrolysers, each being around 40 meters long, with the hydrogen subsequently converted to ammonia to ease shipping.

The cost of the plant has been reported at $5 billion, with sales of hydrogen expected to commence in 2026[8]. Using this data, the levelized cost of hydrogen (LCOH[9]) can be estimated, which provides a method of comparing the costs of different technologies over the lifetime of a plant. In this case, and when assuming an operating cost of $150m per annum growing at 3%, a hurdle or discount rate of 10%, 350 days per year operation time per annum and a project lifetime of 30 years, the LCOH is estimated as $3.42/kg. This value can be converted to £2.83/kg or £71.89/MWh using the appropriate conversion factors ($1.21=£1:00 and 0.03937 MWh/kg) and compares favourably with that reported in the BEIS Hydrogen Productions (2021) costs which range between £178/MWh and £58/MWh depending on electricity pricing for similar electrolyser technology. Again, the sensitivity can be explored and here, it was estimated that increasing the operating costs for the NEOM project from $150m/a to $300m/a increases the LCOH £89.94/MWh.

The above analysis can also be used to provide an approximate cost as well as the scale by using an offshore location such as that identified for the cancelled First Flight Wind project (54.086°N, -5.634°W). Here an increased capacity factor of 56% is found, and if using the higher heating value, it is estimated that 8.3 GW of offshore wind would be required, which, if directly scaled to the cost of the NEOM project, results in a value of $10.4bn. Similarly, it was estimated that 58 sq miles would be required to deploy 600MW at the First Flight Wind site, which would scale to 802 sq miles in order to deliver the required 8.3 GW, which is an area larger than the Northern Ireland offshore water. While the scale of the power system to deliver hydrogen (the simplest e-fuel) is significant, it is noted that the UK Energy Security Strategy increased the offshore wind target to 50 GW from 40 GW by 2030 in the Net Zero Strategy with up to 125 GW installed by 2050. At the same time, SONI estimated that only 0.85 GW of offshore wind by 2040 would be available in NI under their accelerated ambition scenario[10] , and therefore, there is a significant gap in what would be required to meet 2019 demand and what is expected to be reasonably deployed.

[7] *Estimated from https://www.renewables.ninja/ for Latitude 28°, Longitude 35.15°*

[8] *https://www.bloomberg.com/news/articles/2022-03-17/saudi-arabia-to-start-building-green-hydrogen-plant-in-neom*

[9] *BEIS Hydrogen Production Costs 2021*

[10] *SONI Tomorrow's Energy Scenarios Northern Ireland 2020*

4.1.2 Hydrogen based synfuels

Hydrogen is not the only energy storage vector for synfuels. However, it is a significant energy carrier which can then be stored using other elements such as carbon or nitrogen. For example, as pointed out above, the NEOM project intends to export hydrogen in the form of ammonia which is produced by the following chemical reaction

1. $N_2 + 3H_2 \text{--->} 2NH_3$

This reaction is carried out industrially using the well-known Haber-Bosch process and is attractive in that the ammonia product is significantly easier to store and transport than compressed or liquid hydrogen. One impact of adding a relatively inert material (nitrogen) as a carrier is that the energy density is significantly reduced, from a lower heating value of 120 MJ/kg for hydrogen to 18.64 MJ/kg for ammonia. Secondly, the above reaction is exothermic, meaning that energy is released during the process, and therefore the energy associated with the hydrogen in the final product is lower. In this case, ammonia contains 17.65% by weight hydrogen and adjusting the LHV for ammonia based on the hydrogen content only yields 105.6 MJ/kg hydrogen, i.e. a 13.6% reduction relative to the pure form.

Carbon is an alternative hydrogen carrier which can also be used as a hydrogen storage material through reactions such as the following to produce methane.

2. $C + 2H_2 \text{-->} CH_4$

In this case, the methane has a lower heating value of 50 MJ/kg as the hydrogen content is 25 wt%; adjusting the LHV for hydrogen yields 200 MJ/kg, which is in excess of pure hydrogen. While this reaction is also exothermic, meaning that heat is generated during the process, the carbon also contains energy and can act as a fuel when combusted to yield carbon dioxide. This carbon energy is more than enough to account for the energy transfer in the process and results in a product (methane) which has more energy than the hydrogen used to make it.

An alternative to reaction 2 is to utilise CO_2 rather than carbon. In this case, the reaction becomes

3. $CO_2 + 4H_2 \text{-->} CH_4 + 2H_2O$

This reaction is known as methanation (also relates to CO conversion to methane) and, like the ammonia and methanation reactions, is exothermic, meaning that some energy is released during the process and not captured by the products.

As before, the LHV for methane based on the hydrogen weight fraction is 200 MJ/kg; however, unlike reaction 2, only half of the hydrogen results in methane, with the remainder converted to water. In this case, 0.5kg of hydrogen is needed to produce 1 kg of methane, meaning that 60 MJ (120 MJ/kg of hydrogen) resulted in 50 MJ of energy for the methane, a drop of 16.7%.

Reaction 3 can also be used to produce much heavier liquid fuels such as octane (C_8H_{18}), a primary component in gasoline. Here the equation is as follows

4. $CO_2 + 25H_2 \text{-->} C_8H_{18} + 16H_2O$

As before, the reaction is exothermic, meaning that some of the hydrogen energy is not embedded in the final product, but this has the advantage of being a drop-in replacement for petrol. Similar equations exist for diesel, jet fuel etc., and the technology for this will be discussed in later sections.

The previous 28,833 GWh of energy can be converted to an equivalent mass of octane, which has a lower heating value of 44.42 MJ/kg and yields a value of 2340 kt. Noting the balanced chemical reaction to produce octane from hydrogen and CO_2 described in equation 4 and converting to weight shows that in order to produce 1 kg of octane, 0.44 kg of hydrogen is needed along with 3.08 kg of CO_2. Therefore, when using octane as a carrier rather than pure hydrogen, the total annual hydrogen requirement increases from 865 kt to 1025 kt. More detailed analysis by Shah et al.[11] who recently investigated the potential of sustainable aviation fuels to decarbonise the aviation sector within Spain, calculated that 0.57 kg of H_2 is required per kg of jet fuel product due to the consumption of hydrogen within the process to meet the thermal demand. Within their analysis, 251 GW of solar energy was needed in Spain when using a capacity factor of 13.5% to produce 6470 kt of Jet fuel per year alongside 1938 kt of by-product gasoline. It is recognised that the combined total of these (8408 kt) is significantly greater than the 2208 kt required to meet the demand in NI and that the reported capacity factors are lower than that typically found in NI for renewable wind energy (56% for first Flight Wind). Adjusting for these factors still suggests that around 14.3 GW of renewables would be required to deliver the 2019 demand of 2208 kt of petroleum products per annum (requiring 1275 kt of Hydrogen).

The above reactions (1 to 4) all relate to e-fuels, whereby hydrogen produced by electrolysis is the major energy carrier and where either nitrogen or carbon are used to facilitate storage.

[11] *DOI: 10.1039/d1ee03437e*

It is also clear that when energy-neutral materials are used to store the energy (N_2, CO_2), the exothermic nature of the storage reactions will lead to an effective energy loss in the final product. The extent of the loss will relate to the processing technologies used; nevertheless, some will occur. While it would appear that using chemical methods to store the hydrogen energy in the form of larger synthetic fuels is inefficient due to thermal losses in the reactions, it should be pointed out that compression of hydrogen also results in significant thermal losses. Hydrogen compression is an energy-intensive process requiring around 21 MJ/kg to achieve 700 bar. When taking these losses into consideration, as well as the increased costs associated with high-pressure storage, chemical energy carriers such as synthetic fuel production becomes increasingly attractive.

4.1.3 Biogenic carbon-based fuels

While the Carbon in the reactions above could come from any source such as combustion products or Direct Air Carbon Capture (DACC) of CO_2, in NI we have substantial levels of biogenic waste and non-waste streams which offer potential for the creation of gaseous and liquid fuels. As in the case of reaction 2, the starting material itself can also have an energy value meaning that the final product can have more energy than the original hydrogen used to produce it. This is particularly relevant to NI given that there are significant quantities of wastes available which have an intrinsic energy value and, therefore, could be upgraded to fuels.

For example, consider the following hypothetical reaction between the basic building block of starch (a polymerised form of $C_6H_{10}O_5$) and hydrogen to produce hexane (C_6H_{14}), a gasoline additive and water

5. $C_6H_{10}O_5 + 6H_2 \dashrightarrow C_6H_{14} + 5H_2O$

In this case, 0.163 kg of hydrogen is used to produce 1 kg of hexane, which has a lower heating value of 44.75 MJ/kg. Therefore the 19.56 MJ in 0.163 kg of hydrogen was upgraded to 44.75 MJ in the produced hexane. While this does ignore the inherent energy in the original starch, it demonstrates how hydrogen can be used to treat other (potentially waste) materials to produce higher (energy) value materials which can act as a high-quality fuel.

It is of course, possible to produce hydrogen directly from the starch using a reforming reaction such as

6. $C_6H_{10}O_5 + 7H_2O \dashrightarrow 6CO_2 + 12H_2$

In this case, the starch is reacted with steam to produce both CO_2 and hydrogen in a 1:2 ratio. This reaction is endothermic and therefore requires energy to realise. Here the starch has an LHV of 4.56 MJ/kg, and the reaction would consume an energy input of 13.35 MJ/kg but would yield 0.148 kg of hydrogen with a lower heating value of 17.78 MJ. Furthermore, the products of the reaction could be further processed as per reactions 3 or 4 to produce gaseous or liquid fuels. Overall, there are multiple options by which fuels can be produced, ranging from small molecules such as hydrogen to larger drop-in equivalents for the fuels used today. The above does demonstrate that system inefficiencies can lead to significant increases in energy requirements. For example, the 28,833 GWh requirement could be met by 9.4 GW of renewable electricity at a 35% capacity factor which would reduce to 5.9 GW if a capacity factor of 56% was achieved. However, if used to produce hydrogen at 55 kWhr/kg and using non-condensing combustion technologies (e.g. combustion in a vehicle), the 5.9 GW would only produce 526 kt per annum, which is significantly short of the 865 kt needed. Improved condensing technologies would reduce the requirement to 741 kt, but this does not take into account the energy and cost associated with the storage of pure hydrogen. Using chemical methods of storage such as e-fuels also results in the need for additional energy due to heat losses in the reactions; however, if the species used to store hydrogen has an intrinsic energy value, then this can be used to offset the energy lost and therefore increase the overall energy value with a commensurate decrease in hydrogen need.

Given that many organic wastes have an energy value, this latter point is important, particularly within the context of the NI economy.

4.2 Domestic heating

The Energy in Northern Ireland (2022) report estimated that 7,400.4 GWh of petroleum products were used for domestic heating alongside 3,006.1 GWh of gas, 1,869.6 GWh of bioenergy, 435 GWh of coal and 319 GWh of manufactured fuels. The latter being defined as any solid fuel made from coal, wood, plant-derived materials, waxes or petroleum products, mixed with other ingredients[12]. Fossil based fuels therefore account for approximately 10,841 GWh with oil having a 68% share.

During the transition to net zero the number of gas grid connections in NI is expected to initially increase and by 2030 the sector is predicting that gas demand will rise to around 9,140 GWh. Assuming the same split between domestic and industrial users, a housing growth of 8% over the period[13] and no change in terms of renewable heating alternatives suggests that oil demand could increase to 8,319 GWh by 2030. Clearly factors such as insulation and uptake of low carbon technologies will impact this value. However, it is likely that there will be a need for a heating oil replacement unless significant incentives or similar are made to encourage uptake of heat pumps which will ultimately transfer demand, albeit lower, to the power sector.

In the absence of incentives to switch to electrical based heating the natural turnover of boilers which can operate on alternative fuels becomes important. In April 2022, the total housing stock in Northern Ireland was 822,083[14], if each housing unit is assumed to have one boiler and these are replaced every 15 years then approximately 54,800 boilers are replaced per annum thereby offering an opportunity to switch to an alternative fuel rather than a drop-in replacement such as HVO. While HVO could be used it is also applicable to the transport and aviation sector. Therefore, this fuel and similar products are not likely to have significant penetration within the home heating market as the feedstocks will increasingly be directed to other markets prepared to pay higher prices. At the same time the process for the production of hydrotreated oils to produce diesel or aviation fuel also produces a renewable LPG equivalent which can be directed towards the domestic heating market.

While Hydrogen is an important e-fuel it is unlikely to be suitable for off-grid domestic heating due to the low volumetric energy, for example at 25 °C and 300 bar the density of pure hydrogen is 20.537 kg/m3. Therefore, while the higher heating value of heating oil (43 MJ/kg) is significantly lower than hydrogen (141.7 MJ/kg) this low density would mean that 1000 L of heating oil would require a volume of high-pressure hydrogen which is 13 times larger to be equivalent in terms of energy. As such, **while hydrogen may be used within the gas grid it is unlikely that it will have any significant demand in off-grid domestic applications.**

Given the above, three fuels are likely to adsorb the bulk of domestic heating market by 2050, namely biomass, renewable LPG (rLPG) and renewable DME (rDME). Here biomass relates to an increase in penetration of wood pellet boilers while rLPG relates to either gas produced as a by-product of vegetable oil/tallow hydrotreating or a light fraction produced during the Fischer-Tropsch process, and rDME which is produced as an alternative to methanol. While methanol will also be an important fuel (e.g. marine applications) and is liquid under normal operating conditions it is more toxic than DME and hence is unlikely to significantly impact in the domestic market. Similarly, rLPG and rDME can share common infrastructure in terms of on-site storage, transportation and logistics with only minor modifications required for the boilers. Compressed bio or synthetic methane (rCNG) is also an option however it is expected that the bulk of production of rCNG will be in proximity to the gas grid and will use that infrastructure along with hydrogen to decarbonise.

Example:
In May 2022 Dimeta B.V. which is a joint venture between SHV Energy (owner of Calor) and UGI International, announced the intended location of its first commercial-scale renewable dimethyl ether (rDME) production plant at Teesworks in the UK. The company plans to produce 50,000 tonnes/year of rDME which is produced using KEW gasification technology operating on non-recyclable waste.

[12] https://www.gov.uk/guidance/selling-manufactured-solid-fuels-for-domestic-use-in-england
[13] Northern Ireland Housing Statistics 2017-18
[14] https://www.finance-ni.gov.uk/topics/statistics-and-research/housing-stock-statistics

Given the availability of biomass and (fossil) LPG at the present time it is likely that both of these sectors will grow over the next decade by such time rLPG and rDME will become increasingly available and will displace the fossil fuel alternatives. Once production of e-methanol is established rDME is expected to grow faster than rLPG. This is due to several factors including:

- rLPG being a by-product of other markets which face constraints on oil/tallow availability
- DME having a lower greenhouse warming potential and low atmospheric lifetime (5.1 days)

At the same time there will be a push towards the use of heat pump technology. However significant retrofit may be required depending on the nature of the property meaning than uptake will be lower unless incentivisation and supply chain issues are resolved. Boosted or hybrid heat pump technology which allows for lower levels of deep retrofit are likely to be more attractive if the technology, cost and maintenance issues can be addressed appropriately. Geothermal and heat networks utilising waste heat will also impact on overall future demand, but these are expected to be relatively niche and while important are not expected to significantly impact overall demand by 2050.

4.3 Impact of retrofit on heating demand.

Work by Ogunrin et al. investigated domestic energy efficiency scenarios for Northern Ireland[15] with their central option aligning with the CCC's 6th Carbon Budget Balanced Pathway Scenario in terms of measures and percentages of houses proposed for retrofit. Within the manuscript the total domestic heat energy consumption in 12,764 GWh for oil, gas, coal, electricity and renewable fuels with only 54.3% directed towards space heating. The authors central scenario presented a modest and balanced pathway for domestic retrofit in NI and here it was calculated that there would be a drop in demand of 10% by 2050 (6932 GWh to 6253 GWh), however when including demand from new builds this increases to 6882 GWh with retrofit costs estimated at £2 billion. A more ambitious scenario recommending that all of the 2018 housing stock, at a rate of 23,000 per annum, is retrofitted by 2050 resulted in an 18% reduction with annual heat demand of 6209 GWh by 2050 including new build and costed £5.9 billion.

Similarly, the Energy Systems Catapult domestic heat demand study[16] also predicted a decrease in energy required under various scenarios including the impacts of climate change and housing insulation improvements on space and water heating demand. Based on this work the UK space and water heating demand in TWh are presented in the table below and used to estimate the NI contribution (4%) which closely matches the total heating energy demand in NI.

Space	Water	Total	NI ≈ 4% [GWh]
2020	260	65	13000
2030	220	70	11600
2040	175	75	10000
2050	160	75	9400

[15] DOI: 10.3390/en15092985
[16] https://esc-production-2021.s3.eu-west-2.amazonaws.com/2021/07/Domestic-Heat-Demand-Study.pdf

The above predicts a 28% reduction in demand by 2050 whereas the work at Ulster University estimated a lower value of 18%, even when considering significant interventions. At the same time the housing sector is expected to see a level of growth. Overall, a conservative domestic heating market for fuels by 2050 would be a 10% reduction (decreasing linearly) over 2019 figures due to retrofit, boiler replacements and improved quality of new build. Policy instruments such as significantly increased incentivisation for heat-pumps and insulation may accelerate this change but evidence to date from wider UK incentives schemes does not suggest a very rapid shift. However, a reduction in installation costs for heat pumps, increases in fuel prices (e.g. Ukraine) and a better designed and accessible incentive scheme should improve take-up rates if grid capacity is available. It is notable that other European countries have been much more successful with incentivising energy-saving retrofits but at considerable higher levels of support.

It is expected that Coal will be phased out however niche markets will remain and equivalent manufactured fuels which blend biomass and biochar are expected to replace this market. Biomass is expected to increase its market penetration and here an extra 500 kt/a of woodchip at 57% moisture content could be converted to 203 kt of wood pellets at 6% moisture. Assuming a heating value of 19 MJ/kg this results in an equivalent contribution of 1,070 GWh to domestic demand.

The 10% reduction in energy demand with increases in biofuels production can be used to estimate the size of a possible synfuels market in NI by 2050.

	2019	2050
Coal	435	0
Manufactured fuels	319.7220	754.7
Petroleum products	7400.4	0
Gas	3006.1	4000
Bioenergy	1869.6	2939.6
Synfuels	0	4033.4
	13030.8	11727.7

In this case 4033 GWh of energy from synfuels is required. Tallow and waste oils would not be available in sufficient quantities to meet the above synfuel demand and hence rDME is attractive. Using a higher heating value of 21.1MJ/L this would equate to 682 million litres of DME per annum (approx. 457 kt). Any decrease in the availability of synfuels will shift demand back to petroleum products with alternatives to decarbonisation such as off-setting being used to attain an overall decarbonised product.

4.4 Overview of processes for fuels production

Figure 2 below provides a simplistic overview of various processes which would accompany the production of carbon-containing bio or synthetic fuels. Here the feedstock is any carbon-containing stream, including air, flue gas, biogas, organic sludges, refuse-derived wastes etc. For each feedstock, some level of pre-processing would be required, which includes technologies needed to concentrate the required species (e.g., DACC or similar to increase the CO_2 concentration), the removal of problematic species which would negatively impact downstream processes (e.g., poisons such as sulfur) or a change in the physical nature of the feedstock (e.g., size). In the case of refuse-derived fuels (RDF), simple pre-processing techniques such as size adjustment and removal of contaminants would be sufficient to generate a product fuel. In many other cases, the cleaned and pre-processed feed would be sent on to primary conversion. This could include biological, chemical, or thermal treatment to produce a product used in subsequent processing. For example, fermentation processes could be used to produce biomethane, bioethanol or biohydrogen, while thermal processes such as pyrolysis or gasification would convert the feedstock into a range of smaller products for subsequent conversion. Similarly, chemical methods such as hydrotreating can convert the feedstock into a range of products. In each case, a mixture of products is normally produced, some of which may be undesired and hence need to be removed. In cases such as syngas (a mixture of CO, CO_2 and H_2) which is produced via pyrolysis or gasification, the ratio of gases often needs to be optimised for downstream processing. This can be achieved using technologies such as the water gas shift reaction or using separation to selectively remove a species from the process stream.

Once adjusted, the feed is then passed to a further processing section which can convert it into other more useful products. Example technologies here include methanol or Fischer-Tropsch (FT) synthesis.

Both processes require catalysts, with the latter process performing reactions of the type described by equations 3 and 4 above. Within FT synthesis, a broad range of hydrocarbons is produced, which are then processed in subsequent steps.

Example projects
In 2018 BP and Johnson Matthey initiated a project with Fulcrum BioEnergy to license their FT technology to convert municipal solid waste into biojet fuel at the Sierra BioFuels Plant located in Nevada, USA. The plant uses a simple-to-operate, scalable and cost-advantaged FT technology termed FT CANS to economically convert synthesis gas generated from sources such as municipal solid waste and other renewable biomass into long-chain hydrocarbons suitable for the production of diesel and jet fuels. As of May 2022, the Sierra Biorefinery began processing prepared waste feedstock and has successfully produced high-quality hydrocarbon syngas for conventional Fischer-Tropsch fuel production. Within the UK, similar technology is being proposed within the Fulcrum Northpoint project, which is expected to convert non-recyclable and residual wastes into around 100 million litres of SAF per year for use by airlines operating at UK airports. At present, this project is in the planning application stage.

In some cases, the initial conversion produces materials which are suitable to pass directly to the clean-up stage, whereas in other processes, the product will require further conversion. An example here is where methanol is produced in the initial reactor but converted to heavier hydrocarbons using, for example, methanol to gasoline technology. Within the clean-up phase, distillation or other separation techniques are used to produce fuels of the correct quality for sale.

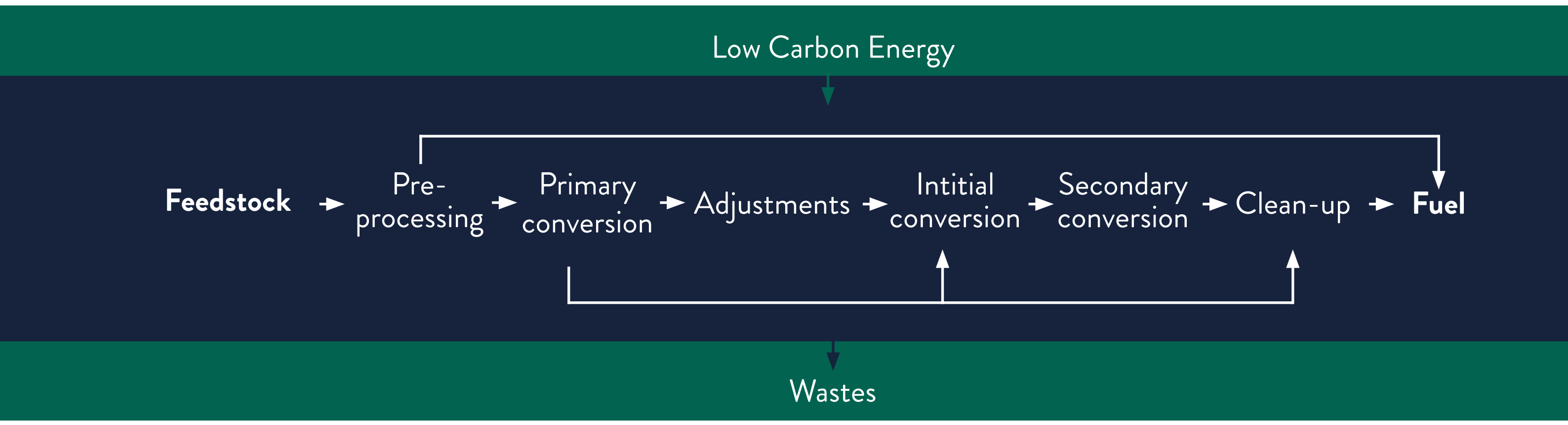


Figure 2 Schematic overview of synfuel production

Each process will also result in either an energy input or output which will depend on the nature of the reaction or separation required. As described earlier, some reactions will be exothermic therefore requiring cooling, whereas some will be endothermic, thereby requiring heating. Where possible, energy flows should be matched to balance the energy and reduce overall consumption. Thermodynamic limitations will, however, mean that energy is likely lost as low-grade heat, and hence investigating options whereby this heat could provide value (e.g. heat networks or others) is desirable from an overall energy-saving perspective. Similarly, some processes could be enhanced using simple e-fuels such as hydrogen by directly incorporating electrolysis into the overall system design. Furthermore, each process may produce physical wastes which may or may not be able to be recycled.

It is very important to consider the thermodynamic limitations associated with each conversion technology. One example would be to consider the production of Dimethyl ether (DME or $(CH_3)_2O$) from green hydrogen and biogas, which has been used as a diesel replacement due to its high cetane number. The hypothetical reaction for this is as follows

7. $CH_4 + CO_2 + 2H_2 \dashrightarrow 2(CH_3)_2O + H_2O$

In this case, biogas at a 50:50 blend is mixed with green hydrogen to produce DME and water. Alternatively, some of the biogas could be steam reformed to produce hydrogen; however, this would be less efficient than electrolysis. The above reaction is mildly endothermic, meaning that to produce DME, the system would require an energy input of 0.924 MJ/kg of product. However, there is currently no single reaction chemistry which can achieve the above, and in reality, the production would be carried out in at least two steps. Firstly, the biogas would be converted to syngas as follows

8. $CH_4 + CO_2 \dashrightarrow 2CO + 2H_2$

And secondly, this would be blended with additional hydrogen before conversion to DME[17]

9. $2CO + 4H_2 \dashrightarrow 2(CH_3)_2O + H_2O$

The net sum of these reactions would equal that described by equation 7. In terms of processing, reaction 8 would be carried out at low pressures and high temperatures and is very endothermic (247 kJ/mol CH_4), whereas the second reaction step would be at high pressure, much lower temperatures and is highly exothermic (-205 kJ/mol DME). As the lower temperature of the second reaction cannot be used to energise the first (i.e., an object at 200 °C cannot heat an object at 800 °C), the energy would be lost unless it was used in other processing steps. This example case demonstrates the need for careful consideration of the overall process required to produce synthetic fuels and the need to evaluate opportunities to match processes so that they can maximise energy storage.

In the above, a range of process technologies was provided, and the following section describes some of these in more detail.

[17] *This reaction would normally produce methanol first followed by dehydration to DME. However, the two catalyst systems can be blended. As such only one reaction is presented here.*

4.4.1 Pyrolysis

Pyrolysis is a thermal process that involves the degradation of biomass in an oxygen-free environment at temperatures between 300 – 900°C. The process generally yields three distinct products; a solid fraction referred to as biochar, a liquid fraction (biooil) and a gaseous fraction. The end product yield distribution and properties are a function of feedstock characteristics and process parameters, such as temperature, heating rate, residence time, particle size, and type of reactor used, with results generally in the range of 20-30% gas, 27-55% liquids and 10-25% solid. The mechanism behind the pyrolytic degradation of lignocellulosic material is complex, and in practice, many reactions take place in parallel and series. This includes dehydration, depolymerization, volatilization, charring, aromatization, decarboxylation, cracking, repolymerization and condensation. The literature presents a general consensus that biomass pyrolysis follows three main stages:

i. initial dehydration
ii. primary decomposition

Thermal degradation of biomass usually occurs during the primary decomposition stage at 200 - 400°C, forming a solid char which is followed by secondary reactions as the temperature increases, promoting further volatilization.

In terms of fuel value, each of the product streams contains energy. The gases are generally a mixture of methane, ethane (C_2H_6), CO, CO_2 and H_2, whereas the solid (char) has a high concentration of carbon, which could serve as a coal replacement. The liquid fraction comprises a mix of acids, carbohydrates, aldehydes, ketones, lignin fragments, aromatics, and alcohols. While these have energy value, the quality and composition of the produced stream make it difficult to process, thereby limiting its use. Methodologies to improve the quality of the biooil have been explored, including deoxygenation technologies, but significant challenges remain, and as reported by Venderbosch, the reactions needed to yield improved quality of liquids may be practically impossible.[18]

[18] *DO:10.1002/cssc.201500115*

4.4.2 Gasification

Gasification is an alternative thermochemical conversion that is usually carried out at a temperature ranging from 700-1000°C in a partially oxidized environment, using air, steam or oxygen. While the main products of gasification are similar to pyrolysis, this process favours the production of syngas. The literature reports a typical yield of ~5, 10, and 85% for char, oil and syngas, respectively. The low char yield achieved via this route deems this technology more suited to energy and the production of various chemicals that are synthesized from syngas. The IEA Hydrogen from biomass gasification report[19] provides a comprehensive overview of ways to produce hydrogen via gasification routes using both steam gasification and sorption-enhanced reforming. Within the report, it was noted that hydrogen efficiencies (LHV based) of up to 69% are achieved, and a techno-economic study shows hydrogen selling prices of down to 2.7 € kg^{-1} (or 79 € MWh^{-1}). A range of different technologies are described, including dual fluidised bed technology, which, when using woody biomass as a feedstock, produces a gas which is composed of H_2 (35-45%), CO (22-25%), CO_2 (20-255), CH_4 (≈10%), C_2H_6 (2-3%) and 20-30% tar. One of the critical factors associated with biomass gasification is tar control which can lead to problems with build-up on heat transfer equipment and failure of the system.

Example
The University of Ulster have been investigating the conversion of waste biomass resources through downdraft gasification to generate a producer gas for combined heat and power. Studies included feedstock analysis, process modelling, and experimental analysis in a pilot-scale fixed-bed downdraft gasifier. Anaerobic digestate and miscanthus were compared to the gasification potential of poultry litter with a case study based on a typical poultry farm in Northern Ireland. Results found producer gas with a lower heating value up to 4.15MJ/Nm^3 can be generated, and that downdraft gasification coupled with cogeneration could have a payback period of 4 - 5 years given the correct conditions. The net present value was positive for all technologies considered (i.e. internal combustion engine and the Organic Rankine cycle combined heat and power unit. The break-even selling price was also estimated to be lower than the current grid electricity selling price (£120/MWh) when incentives such as i) avoiding disposal cost of £30/tonne, ii) selling the biochar by-product at £200/tonne and iii) fuel displacement costs of 1.5p/kWh were considered.

[19] *IEA Hydrogen from biomass gasification (2018)*

4.4.3 Aqueous phase reforming

It is recognised that the bulk of waste feedstocks in Northern Ireland are non-volatile and wet, particularly agri-wastes and also sewage sludges which contain significant quantities of water. In such cases, aqueous phase reforming (APR) represents an alternative to pyrolysis or gasification options, as here, the reforming reactions are carried out in high-temperature, high-pressure water (200-270°C and 15-60 bar). A recent review by Zoppi et al.[20] critically discussed experimental research aimed at valorising complex feedstocks, such as real waste streams or synthetic mixtures, using APR and highlighted the limitations for the full development at an industrial scale. Within their review, it was identified that APR could outperform other technologies such as AD. For example, approximately 294 m^3 H_2/t COD (Chemical oxygen demand) was obtained with APR vs 150 for the anaerobic digestion of brewery wastewater. This is not surprising given that the AD process is biological rather than chemical and where the biological to chemical oxygen demand ratio would be approximately half.

Techno-economics is also important, and here the authors presented an analysis of hydrogen production from glycerol reforming (a byproduct of biodiesel production) and estimated a cost of $3.65/kg cost for steam reforming vs $3.55/kg for glycerol APR. These values compared well with other renewable hydrogen routes, such as biomass gasification ($1.77–$2.05/kg), dark fermentation ($2.57/kg), and solar thermal electrolysis ($5.10–$10.49/kg). The authors, however, highlighted that the cost of the feedstock could significantly impact the overall economics. The example of a 500 kg/h hydrogen plant from sorbitol to supply a 100 kt/a green diesel plant was given, and where it was identified that the hydrogen production costs would be approximately $13/kg and that the feedstock would account for 92 % of the total production cost. In addition to feedstock price sensitivity, the need to design cheaper catalyst formulations to improve the overall cost-effectiveness of the process was highlighted. Again, it was identified that industrial synergies would further assist in the production of useful synthetic fuels. For example, the integration with dimethyl ether (DME) production, whereby the exothermic DME reaction may be used to offset the endothermic APR reaction as in this case, the temperature is closely matched.

4.4.4 Biohydrogen through dark fermentation from organic wastes

Two important methods for biohydrogen production include photofermentation and dark fermentation, both of which utilize microbial resources. In the presence of light, the production of hydrogen is accomplished by various photosynthetic microorganisms, whereas in dark fermentation, the complete absence of light requires alternative biology. Dark fermentation requires more complex organic substrates, for example, lignocellulosic biomass, carbohydrates, sugar or starch-containing crops or organic residues from wastewaters, to serve as the food source for the microorganisms whereby they convert the sugars into volatile fatty acids and hydrogen at relatively low yields (i.e., moles of $4H_2$ per mol of glucose) which is equivalent of 44 kg H_2/t glucose.

Experimental work has shown that the value of 4 mol H_2 per mol glucose is lower in reality, and the review by Sarangi and Nanda summarised the results of a range of biological hydrogen production technologies alongside their process parameters[21]. Here the values reduced from 4 depending on the nature of the feedstock, for example, Hydrolyzed potato peels (3.4), wood fibre (1.47), cornstalk (1.2) and cellulose (1.36). As in the case of APR, the economics of the process are impacted by the system design as well as the feedstock costs.

[20] *IEA Hydrogen from biomass gasification (2018)*
[21] *DOI:10.1016/j.cattod.2021.06.002*

4.5 Alignment with the NI agri-tech sector

Northern Ireland is a significant producer of agri-food products, with the food and drink processing sector achieving a gross turnover of £5,365m in 2019 predominantly from the sale of animal-based products (77% mainly from the sale of meat, milk and milk products and eggs), and fruit and vegetables (7%)[22]. Agricultural by-products and organic wastes/residues are also a result of agricultural production (e.g. plants, sludge, manure) and food processing activities, which need effective and efficient management to reduce waste management costs and environmental pollution. While bespoke energy crops could be used to supply fuels, it is also recognised that the wastes associated with the agri-food sector have an intrinsic energy value that could be used to offset the total energy demand.

There are several different scenarios which could exist for the production of synthetic fuels, and a full analysis and comparison of each scenario is outside the scope of this report. Nevertheless, it is useful to investigate the potential scale of the interventions which could be required to deliver a range of fuels. One such scenario is that which is designed to run parallel to the agri-tech sector and complement existing infrastructure. In this scenario, feedstocks are directed to AD for the production of biomethane with residual matter sent for further processing, including thermochemical conversion, which can be enhanced by hydrogen where the CO_2 is used as a hydrogen storage vector to produce e-fuels.

Herein a variety of sources of feedstocks, including agri-tech and other organic wastes, are used to estimate the carbon availability. Based on an earlier analysis of feedstocks,[23] it was estimated that Northern Ireland Water produces 37,000 tonnes/year of sludge dry matter, which equates to 10.5 million Nm^3 of biomethane when using typical conversion. Similar estimates for biomethane from food and garden waste would yield an additional 17.9 million Nm^3, whereas manures and underutilised silage could produce 253 and 500 Nm^3 of biomethane, respectively, depending on capture rates. The total value of 781 million Nm^3 of biomethane (assuming 97% methane at an LHV of 35.8 MJ/Nm^3 for pure methane) results in an energy content of 7,354 GWh or 26.1% of the overall baseline demand.

Assuming that the composition of biogas is 60% methane and 40% CO_2, with the biomethane being 97% methane and 3% CO_2, then the quantity of CO_2 available for conversion would be approximately 482 million Nm^3 or 945.5 kt. Using the conversion values of Shah et al. for CO_2 to fuels (3.35 kg/kg) and a hydrogen consumption of 0.57 kg/kg, the 945.5 kt of CO_2 could be converted to 282.5 kt, which is split over 217.3 kt of jet fuel and 65.2 kt of gasoline. The energy content of this fuel would equate to approximately 3,688 GWh and consume 161 kt of hydrogen. This output would equate to 12.8% of the 2019 baseline demand, with the hydrogen requiring 8,856 GWh of electricity to produce when using 55 kWh/kg. As before, this can be used to estimate the size of an offshore wind farm to produce the equivalent electrical energy demand when using a capacity factor of 56%. In this case, 1.8 GW of wind would be required. Within the work of Mehta et al.,[24] the digestate was also evaluated as an energy source. However, given the wet nature of the stream, it was found that the energy released through the combustion of the gaseous and liquid pyrolysis fractions would match the drying energy required for the solid fraction of digestate which was 1110 GWh_{th}. Interestingly high-grade heat is not required for this drying process, and therefore other waste heat, e.g. from the fuel production process, could be used, allowing for the energy to be captured or used to offset hydrogen usage in the FT process. Hence the 1110 GWh could be used to offset 20.18 kt per annum of hydrogen. Again, the efficiencies of the thermal combustion processes are similar to that used in the production of hydrogen; therefore, the full 1110 GWh is expected to be saved. Combining together and assuming no decrease in the scale of the hydrogen production results in the following;

Product	Energy (GWh)
Hydrogen	1,110
Biogas	7,354
Gasoline	922
Jet fuel	2,766
Total	12,152

[22] *Northern Ireland Food and Drinks Processing Report 2019*
[23] *An integrated spatial mapping, techno-economic assessment and sustainability considerations to understand the potential of biomethane production in Northern Ireland report (2022)*
[24] *DOI:10.1016/j.renene.2022.06.115*

While this may represent only 42% of the 2019 demand, energy savings are expected. If, for example, fuel demand for power is reduced to 80% in 2019, transport to 30% and heating to 40%, then the above value would account for 98% of the overall energy demand. At the same time, this does not account for any growth in the economy, which would increase overall demand. The above represents only one scenario, and further revision is required in order to match the actual demand and product portfolio. The analysis does, however, suggest that a combination of energy savings, significantly more ambition in terms of renewables production, as well as increases in energy capture from agricultural wastes and feedstocks, would significantly impact the consumption of imported petroleum products in Northern Ireland.

Matching production to product demand (e.g. LPG, gasoline, diesel and kerosene) is possible by adjusting the production slate from the FT or similar process. This is important as, at present, almost two-thirds of homes in Northern Ireland are still heated by oil, with coal used as a primary heating source in a small percentage. Similarly, LPG is common for consumers who are not on the natural gas grid as an alternative to heating oil and for cooking.

4.6 OTHER FEEDSTOCKS

4.6.1 Refuse derived fuels

Before leaving this section, it is worth considering other potential feedstocks for fuel production. In addition to petroleum products for energy Northern Ireland imports significant quantities of other carbon-rich materials, which could contribute to a future synthetic fuels industry. For example, Mehta[25] estimated that 217 ± 11 kt of plastics were consumed in Northern Ireland in 2018, with packaging contributing 47% of total consumption while commercial and industrial accounted for 15% and construction 12%. Similarly, plastic waste production in 2018 was estimated at 149 ± 11 kt, of which about 68% was attributed to the packaging sector.

Based on the analysis, it was identified that only 2% of the total plastic waste flow was reused, 49 kt (33%) of plastic waste was recovered for recycling, and plastic waste disposed of using landfill and incineration accounted for 96 kt (65% of the total). Significant amounts of the plastic waste exported would be captured in the export of refuse-derived fuels RDF). Here RDF exports from Northern Ireland in 2021 exceeded 184,634 tonnes which was a significant increase over the 125,776 tonnes exported in 2020[26]. Riberio et al.[27] investigated pyrolysis and gasification of RDF and reported that pyrolysis was more efficient at 750 °C resulting in a syngas energy density of 11.2 MJ/m^3 and a specific gas production of 0.43 m^3 syngas/kg RDF. Together this suggests that the energy associated with RDF exports would be 247 GWh or 0.86% of the NI demand in 2019.

4.6.2 Tallow and waste oils.

Tallow and waste oils also offer an opportunity to produce fuels. The quantities of these are not widely reported; however, it is estimated that approximately to 40kg of tallow could be produced per head of cattle. In 2021, 463,616 cattle were slaughtered in NI, giving an estimated 18.5 kt of tallow. Assuming tallow has a heating value of 40 MJ/kg, this equates to a fuel potential of 206 GWh.

Quantities of used cooking oil (UCO) in Northern Ireland were not available; however, it is possible to estimate a value based on reported national level statistics[28]. Here the total UCO supply potential in the UK in 2015 was estimated at 157 kt per annum, whereas Ireland had a potential of 16 kt per annum. Based on this, approximately 5.5 kt of UCO could be available, which would equate to 61 GWh. Altogether this would account for 1% of the 2019 demand.

[25] *DOI: 10.1016/j.resconrec.2021.106085*
[26] https://www.daera-ni.gov.uk/publications/export-records-rdf-shipped-northern-ireland
[27] *DOI: 10.1007/978-3-319-91334-6_87*
[28] *Used Cooking Oil (UCO) as biofuel feedstock in the EU, CE Delft 2020*

5 FUEL AND TRANSPORT PATHWAYS

KEY POINTS

- This section summarises a review of fuel and vehicle technology roadmaps and presents a summary of the key opportunities for agri-fuel waste.
- The Marine and Aviation sector are likely to have a growing demand for fuels derived from Agri-fuel waste, such as renewable diesel, e-diesel, ammonia, methanol and SAF.
- There is a moderate opportunity to provide fuels to Agriculture, Mining and Construction sectors where the roadmaps indicate renewable and e-diesel fuels may play a strong role in the future fuel mix.
- There is relatively limited opportunity in the short term for road transport until Zero Emission (ZE) fuels begin to dominate the sector from 2035.
- The sustainability criteria of fuels is expected to become increasingly more stringent. Carbon Capture, Use and Storage (CCUS) should be considered for all new fuel production plant.
- It is unlikely that there is sufficient time to fully adopt multiple fuel supply infrastructure before 2050, therefore in the short to medium term drop-in fuels should be supported that utilise existing infrastructure whilst capability and infrastructure is being developed for key markets in Marine and Aviation industries.

Roadmaps present a consolidated vision of expected future technology transition. Roadmaps are developed by a range of stakeholders, often including industry, academia and government. Cenex has assessed a range of transport technology and fuel roadmaps (see Appendix A for references) relevant to the on-road, off-road, aviation, rail and marine transport sectors to identify the likely technology transitions in these sectors on the road to achieving net-zero.
These roadmaps will provide an insight into the sectors that are most likely to have a demand for Agri-fuel waste.

5.1 Technology Terms Used in Roadmaps

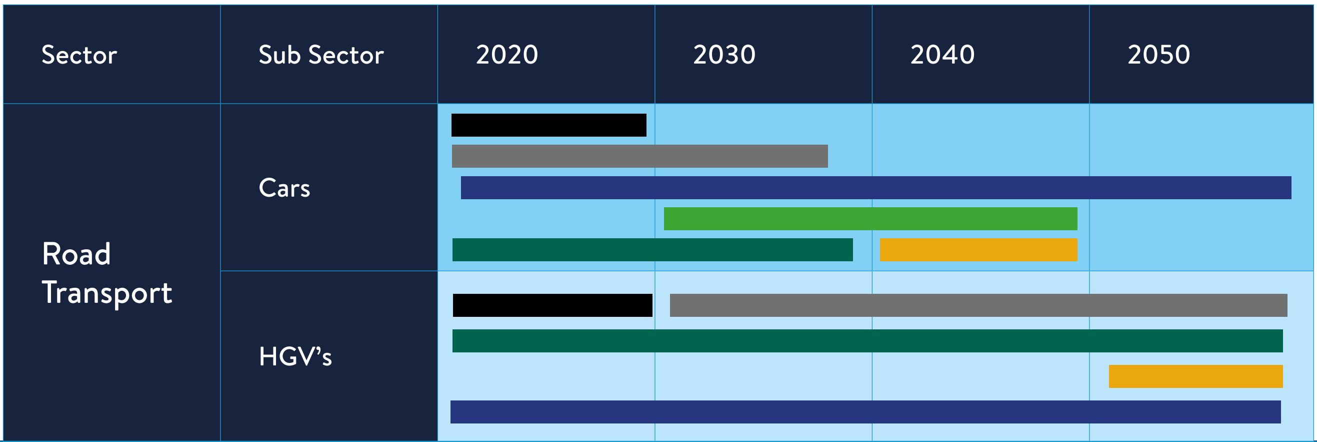
The consolidated roadmaps have been produced using the following technology definitions.

	Description
ICE (Existing)	**Continued use of Internal Combustion Engine** without significant efficiency improvements or technology change.
ICE (Eff.)	Technology based on **improving the efficiency of an Internal Combustion Engine-based drive-train.** These include hybridised systems (electric battery, capacitor, flywheel or other) and improved efficiency and lower emission ICE (implementing best practice and control systems).
Ultra-high efficiency drive	**Radical improvements in propulsion efficiencies** will be achieved through novel technologies from 2040 onwards. These technologies include Liquid Organic Hydrogen Carriers (LOHC) and Solid Oxide Fuel Cells (SOFC).
Electric	**Electric propulsion systems**, include Battery Electric, Hydrogen PEM Fuel Cells (H2-PEMFC), Capacitor, Supercapacitor, Overhead Catenary, Third rail, and Wireless charging.
Operational improvements (OPs)	**Operational practice improvements and efficiency aids.** These include improved aerodynamics, improved power control, demand reduction, consolidation centres, operator efficiency training, hydrofoils, bubble flows, improved propeller design, optimised routing and planning.
Carbon management	These include carbon **offsetting and carbon capture**, use and storage.
Biofuels	**A fuel of biogenic origin.** These may be drop-in fuels such as HVO, biomethane, landfill methane, wood pallets or any other biogenic fuel source. This may include feedstocks which require the removal of impurities and may also require carbon capture to be considered a low emission fuel.
Synthetic fuels	**Synthetic fuels are those fuels where feedstocks (which may include biogenic carbon) undergo chemical processing to alter the chemical makeup.** This includes ammonia, methane, methanol and any other 'e-fuels' that require additional processing. Within this roadmap, pure hydrogen is not included. This category may also include syngas (a blend of methane, carbon monoxide, carbon dioxide, and hydrogen), even though this is typically produced as a waste product. Synthetic fuels may require carbon capture or other processes and are considered to be low emission fuels.

5.2 Roadmaps Summaries

Term	Symbol
ICE (Existing)	
ICE (Eff.)	
Ultra-high efficiency drive	
Electric	
Operational improvements (OPs)	
Carbon management	
Biofuels	
Synthetic fuels	

5.2.1 Road transport



Road Transport Trends

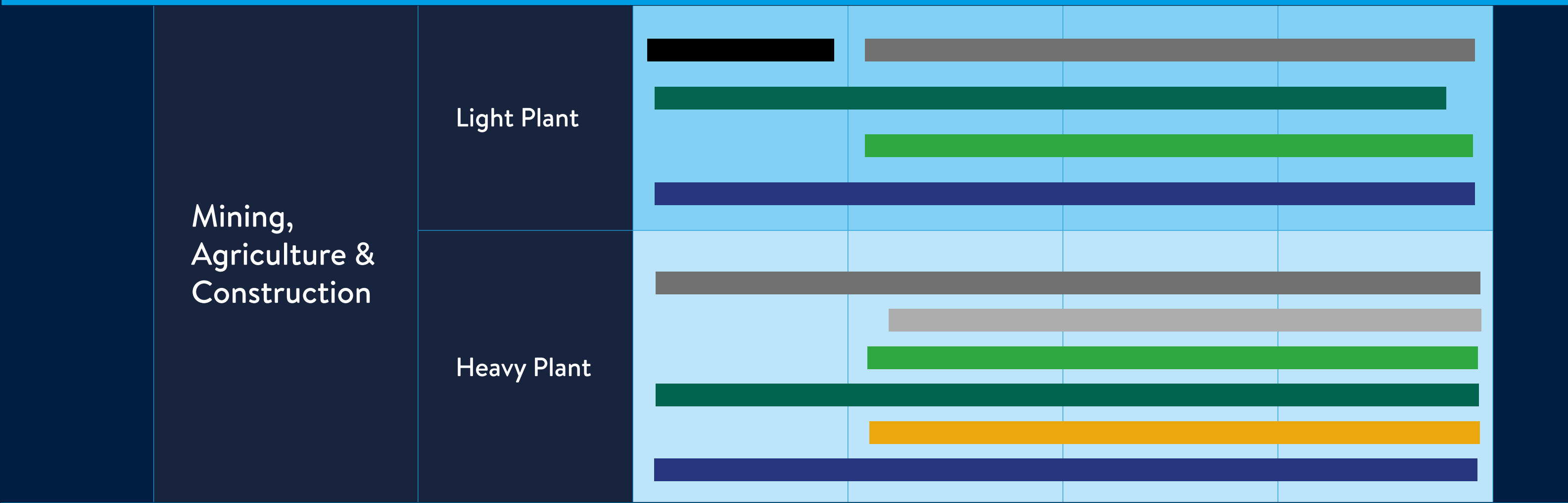
Road transport will see the phase-out of ICE new sales by 2040. Light duty ICE vehicle sales will be banned by 2030, with 2035 seeing a ban on hybrids and non-ZE trucks < 26 tonnes. All non-ZE truck sales to be banned by 2040. InnovateUKs Transport Vision expects a split of 50/50 EV/H_2 drive-trains in trucks by 2050, with all other vehicles being predominantly battery electric vehicles (BEV). Niche and low-volume applications for drop-in fuels such as biomethane and HVO will continue to grow. E-fuels are expected to come to market by 2050.

Key opportunities for Agri-fuel waste products: In the short to medium term, there may be a brief window of opportunity to supply drop-in fuels (e.g., HVO and biomethane) while ZE markets mature. However, the preferred routes for decarbonising UK road transport are clearly dominated by battery electric solutions, with hydrogen-based electrification second place. Niche applications for synthetic fuels will exist in markets such as high-performance, classic and race vehicles. Pure methanol HGVs are undergoing trials, and some companies are investigating dual-fuel ammonia hydrogen engines.

Opportunities for Agri-fuel waste	LOW
	Renewable diesel, E-diesel

5.2.2 Mining, Agriculture and Construction

Road Maps



Off-Road Transport Trends

Unlike for road transport, there is no clear policy direction for agriculture and construction, and mining vehicles and light-duty small plant (under 7.5t) is expected to continue to be electrified. The market for fully electric and hydrogen plants in larger applications is also expected to be niche. Large plant equipment is adopting HVO and other biofuels with improved kinetic energy recovery to achieve significant fuel efficiency reduction in the near term (efficient ICE) today, with longer-term plans increasing the use of biofuels and offsetting through carbon management and potential adoption of hydrogen combustion and ZE technology in the future.

Agricultural sectors look to reforestation as a key component of net zero compliance. Mining sectors are looking at the increased use of alternative and synthetic fuels, but with no clear plan in evidence at the time of writing (all technologies still under consideration).

Ever increasing engine efficiency, the use of bio and synthetic fuels, and the use of hydrogen, ammonia and methanol (in conjunction with carbon capture and use) are all proposed as potential solutions for heavy-duty mining and agriculture equipment. Improved engine efficiency and the longer-term adoption of ultra-efficient engines are integral to the decarbonisation plan of this sector.

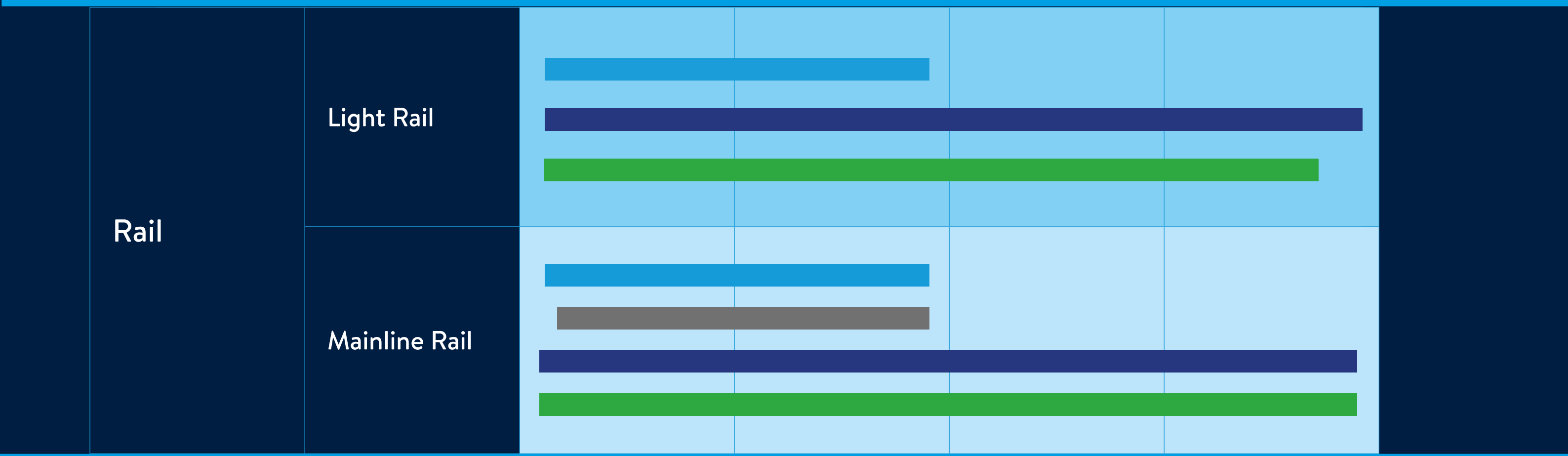
Opportunities for Agri-fuel waste	Moderate
	Renewable diesel, E-diesel

Direct replacement for diesel in ICE engines, with a proven greenhouse gas (GHG) emission saving, is a burgeoning market in plant equipment. HVO is in regular use and growing in popularity. As the demand for HVO reaches saturation point, other low carbon fuels can expect increasing demand from this sector. It is important to note that to date, Non-Road Mobile Machines (NRMM) emissions have been dominated by air quality pollution concerns and not by carbon emissions. Construction equipment used in urban environments is detrimental to air quality and noise pollution. As such, zero-emission at the tailpipe becomes an attractive option when bidding for construction projects in urban environments. Underground mining operations are also actively researching zero-emission powertrains (with limited success to date) to minimise heating, ventilation and air conditioning (HVAC) costs. A cost-competitive e-diesel would still make significant inroads in both the mining and construction sectors for open cast mines and non-urban construction.

Key opportunities for Agri-fuel waste products:
Significant and continued use of both biofuels and synthetic fuels are predicted by several commentators in the plant-equipment sector. In the short and medium term, there may be an opportunity to provide drop-in fuel (incl. biomethane) replacement to existing diesel-power plants.

5.2.3 Rail

Road Maps



Rail Transport Trends

In the UK, direct electrification of the busiest rail lines is the stated policy. The exact rate and scale of electrification have yet to be defined beyond achieving net-zero by 2050. The Committee on Climate Change's (CCC) sixth carbon budget calls for up to 60% of the UK rail network to undergo direct electrification, with the remaining 40% being serviced by a combination of battery or hydrogen-powered train systems.

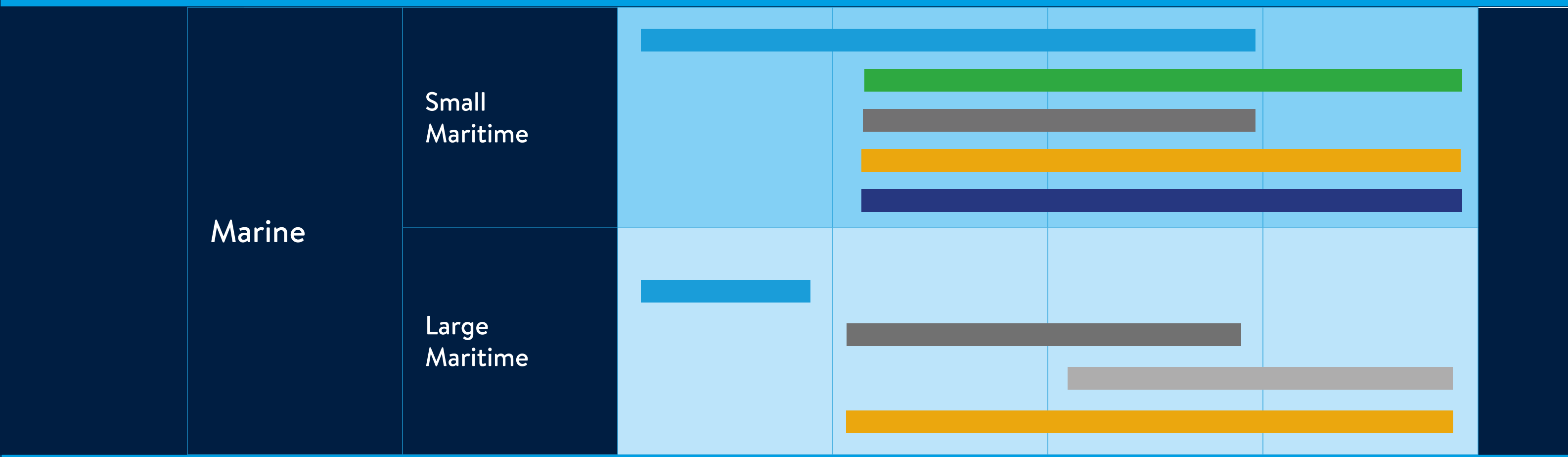
There are no long-term plans for the adoption of synthetic fuels in the UK rail network.
Globally electrification of rail has proven cost-effective on lines with high footfall and a significant number of trains. Hydrogen is expected to play a role in rural areas where line electrification is uneconomic.

Opportunities for Agri-fuel waste	LOW
	Renewable diesel, E-diesel

Key opportunities for agri-fuel waste products:
Older stock and specialist vehicles may still require some support from fossil fuels out to 2050. However, existing plans remaining fossil fuel use in UK rail networks are strongly focused on 'net zero' solutions such as reforestation. HVO and e-diesels may find some niche applications in the rail sector.

5.2.4 Marine

Road Maps



Marine Transport Trends

A clear decarbonisation plan for marine vehicles is yet to be developed. The existing International Maritime Organisation (IMP) plan states a target for a 50% reduction in GHG across the sector by 2050. International shipping is expected to achieve 70% reductions, allowing the coastal and short-sea craft to decarbonise more slowly. It is anticipated that significant emissions reductions will be achieved through a combination of improved engine efficiencies, improved hull design, and improved operational performance. The Maritime sector is a complex field with a very wide range of vessel duties and types. To facilitate this analysis, the sector has been broadly categorised into smaller and larger vessels.

Direct electrification of smaller vessels (under 12 meters) is broadly accepted as likely. Direct electrification of larger vessels operating on fixed routes with a total journey distance of less than 30 nautical miles (nm), e.g. ferries, is an area that has already seen some battery electrification success. The single largest topic of research for maritime decarbonising with projects underway at the moment is hydrogen propulsion systems.

[29] *https://www.maritime-executive.com/article/first-chinese-built-methanol-fueled-tanker-begins-sea-trials*
[30] *https://www.offshore-energy.biz/worlds-first-ammonia-ready-vessel-delivered/*

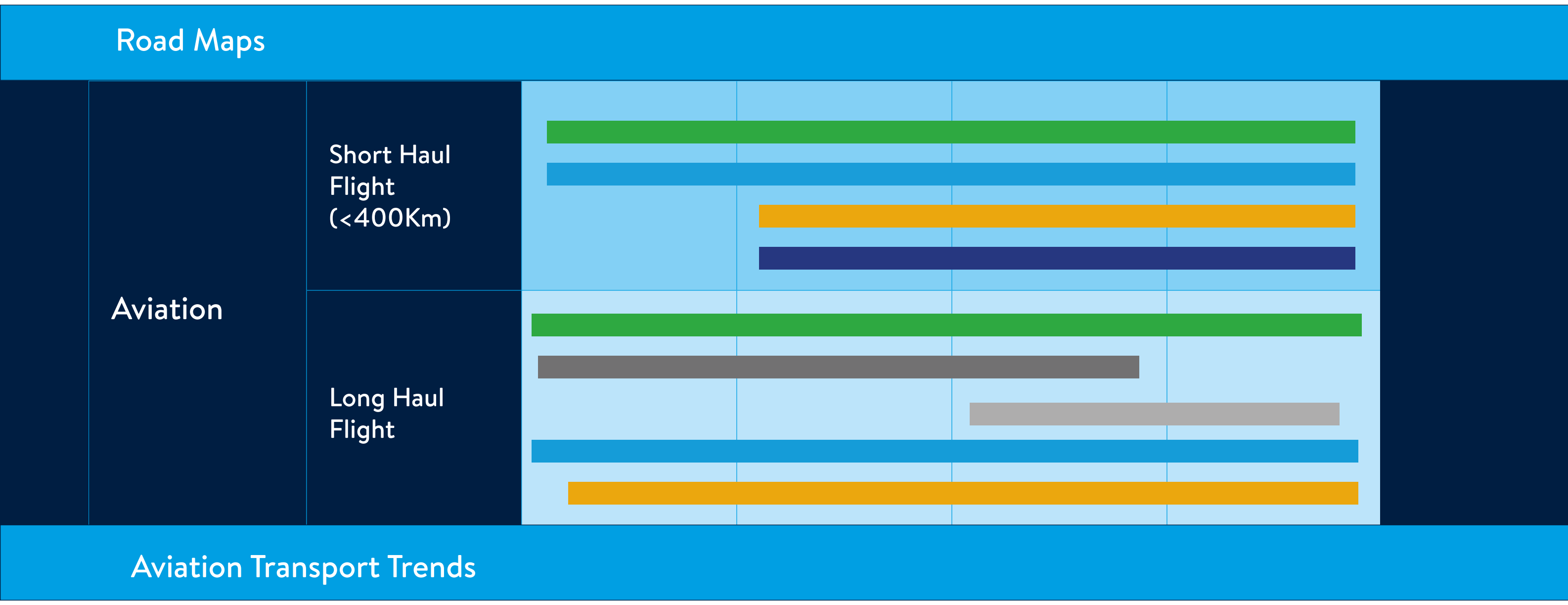
However, these tend to be focused on smaller vessels (albeit greater than 12m in length, with journey distances greater than 30 nm, but no larger than 10,000 tonnes). For the largest vessels, ammonia and methanol combustion are the topics of most interest, though it must be stated that all possible fuels are undergoing trials.

Typically, marine fuel oils are some of the lower-cost fuels on the market. Any effort to displace the various fuels used in the maritime sector is likely to meet a significant price barrier when entering the market There are some areas (such as the Scandinavian coast) where more stringent emission legislation is to be applied. In addition, the contribution for port traffic to poor air quality is under ever increasing scrutiny. There is a broad acceptance that the IMO 50% target will not be considered sufficient and that more stringent legal requirements are inevitable. Significant investments in alternative fuels are underway. However, once again, there is no clear consensus.

Key opportunities for Agri-fuel waste products:
Small and large maritime vessels have synthetic and biofuels in their decarbonisation plans across multiple scenarios. Methanol and ammonia are both being trailed for large container vessels[29, 30]

Opportunities for Agri-fuel waste	HIGH
	HVO, ammonia, methanol, e-diesel

5.2.5 Aviation



The UK government's Jet Zero consultation process is still underway. Internationally, the IATA (International Air Transport Association) has committed to achieving Net Zero by 2050.
Net zero policies such as carbon offsetting, for example, International Civil Aviation Organization's (ICAO) Carbon Offsetting and Reduction Scheme for International Aviation (CORSIA), are a key pillar for the early decarbonisation of international flights.

The opportunity for improved jet engine efficiency is substantial in a global context. Jet turbines have an operational lifetime of up to thirty years (with regular maintenance and periodic overhaul). Engine technologies have improved dramatically over the last thirty. 25% energy efficiency improvements are entirely possible simply through the natural replacement of existing, older jet engine technology.

Both long and short-haul flights intend to use synthetic fuels with new ICE engines for the long term. Recent advances in electrified flight (including hydrogen) may reduce the market share in short-haul flights. Rolls Royce currently certifies all new engines as compatible with 50% substitution of synthetic aviation fuel (bioderived kerosene) and claims the latest Ultrafan® engines will also be 25% more fuel-efficient than present-day engines[31]

Improved engine efficiency and the longer-term adoption of ultra-efficient engines are integral to the decarbonisation plan.

Key opportunities for Agri-fuel waste products:
Synthetic aviation fuel underpins all plans to decarbonise international flights.

[31] https://www.rolls-royce.com/media/press-releases/2020/12-11-2020-rr-to-test-100-percent-sustainable-aviation-fuel-in-next-generation-engine-demonstrator.aspx

Opportunities for Agri-fuel waste	HIGH
	SAF

5.3 NI Fuel Infrastructure Implications

Fuel Supply Change - between now and 2050, the route used to produce, store and distribute fuel is likely to change, but it is unlikely that more than one change in vehicle/equipment and infrastructure is possible before 2050. Any argument for introducing new fuels must consider the supporting supply chains, the need to allow 15 years to recoup capital equipment costs, and the need to supply net zero solutions by 2050.

Some sectors expect capital equipment for far longer periods (up to 30 years in the aviation and maritime sectors).

Focus on Long Term Options - the goal of net zero by 2050 is very close in terms of capital equipment lifetimes. Some vehicles, vessels, plant being purchased in 2022 will still be in use in 2050. The supporting infrastructure to keep today's equipment running has a limited time frame to make a return on capital investment. Therefore, all decisions made today must consider the cross-sector changes to achieve net zero will have on fuel and equipment supply chains, depending on the planned return on investment period.

Short-term Use of Drop-in Fuels - drop-in biofuels are an excellent option in short to medium term (primarily when derived from waste feedstocks) and can be used in high penetrations in the medium term. In this case, production plants should be designed to enable switching to aviation fuel production and installing CCS in the longer term. Biofuels production without certified CCS is unlikely to be viable as we approach the net zero 2050 target. Innovation support already exists for drop-in fuels through the RTFO mechanism. Drop-in fuels do not need a change to equipment/ infrastructure. Therefore, drop-in fuels have a natural market advantage. However, most drop-in solutions are not 'zero emission' and do little to improve local air quality (AQ). If GHG and AQ emissions legislation becomes increasingly strict, feedstock storage, processing, distribution, and combustion emissions will come under ever-greater scrutiny.

5.4 Roadmaps Conclusions

The road map review highlights that the Marine and Aviation sector are likely to have a growing demand for fuels derived from Agri-fuel waste, such as renewable diesel, e-diesel, ammonia, methanol and SAF.

There is a moderate opportunity to provide fuels to Agriculture, Mining and Construction where the roadmaps indicate renewable and e-diesel fuels may play a strong role in the future fuel mix. There is a limited opportunity in the short term for road transport until ZE fuels begin to dominate the sector from 2035.

Sector	Relative opportunity	Potential Agri-fuel type
Road transport	Low	Renewable diesel, e-Diesel, Biomethane
Rail	Low	Renewable diesel, e-Diesel
Agriculture, Mining and Construction	Moderate	Renewable diesel, e-Diesel
Marine	High	Renewable diesel, ammonia, methanol, e-diesel
Aviation	High	SAF

5.4.1 Short – Long Term Options for Roadmaps Narrative

Based on the roadmaps, the following paragraphs discuss the potential short to long-term options for Agri-fuel supply in NI.

Short-term (to 2030) options should take advantage of existing infrastructure and end-user technologies as far as possible. A typical example is the use of CNG, or LNG, with a high contribution from biogenic sources of methane. It is important to note that the fossil methane-based ICE may only offer a slight percentage reduction in GHG emissions (10% or less). 100% biomethane equipment is credited with an 80% reduction in total GHG emissions under current standards. Drop-in biofuel fuels such as HVO are an obvious solution for many markets, with a relatively small increase in fuel costs and no changes to existing equipment or supply chains. Increasing competition for biogenic fuels across sectors is likely in this period.

Medium-term (2030 to 2040) should consider steppingstones to the longer-term net zero goals, combined with air quality emission improvements. The HGV ICE market will likely decline rapidly in this period as the 2035 - 2040 ban in HGV ICE draws closer. In this period, ICE for passenger cars will be banned. HGVs, rail, construction equipment, maritime, and aviation will still be addressable markets. Fully biogenic methane sources and infrastructure is likely to reach maximum market saturation. Methane-based systems should be designed to be compatible with other fuels as far as possible (hydrogen, ammonia, or methanol, for example). This will reduce the investment risk for end-users and the supply chains that support them. Biogenic methane suppliers can anticipate ever greater scrutiny for GHG emissions during collection, processing, storage and distribution. CCUS facilities are likely to be required for biogenic methane to maintain its low carbon status

Long-term (2040 to 2050) full net zero compliance for all sectors should be anticipated. In this period, new sales of ICE for HGVs will be banned. Even existing ICE equipment may be banned. If the current trajectory for ever more stringent environmental legislation continues. Increasingly strict environmental legislation may come into effect if net zero alternative technologies prove capable of displacing ICE in these sectors and climate change accelerates beyond expectations. Net zero 2050 may well become net zero 2040. There is also the possibility that the difficulties of reaching net zero targets and climate change fatigue will have the opposite effect, with net zero targets pushed out to 2060. However, significant long-term Capex investments should minimise risk by assuming that net zero legislation will come into effect no later than 2050 and possibly earlier. As government policy now stands, construction equipment, legacy rail, maritime, and aviation may still be an addressable market. The tolerance of air quality impacts for internal combustion engines may diminish, especially in urban environments. Therefore, a significant proportion of construction and maritime markets may be impacted by air quality constraints, even though a full ban on ICE for these sectors may not materialise. The replacement cycles of aircraft engines indicate that significant numbers of in-service aircraft will now be SAF compatible (50% SAF or greater[32] for all aviation engines in use in 2050).

E-fuels (including ammonia) and green hydrogen: Many future fuels will be reliant on hydrogen and carbon sources as part of the production process. Green hydrogen is when hydrogen is produced via electrolysis from 100% renewable energy (typically wind or solar power). The manufacture of net zero e-fuels (which require green hydrogen) is likely to require additional energy expenditure compared to electrolytically produced hydrogen as an energy carrier. However, the preferred fuel for a given market may still be a synthetic fuel; when additional processing costs to create and transport net zero synthetic fuels are lower than the transport and distribution costs for net zero hydrogen directly. The physical properties of hydrogen will limit hydrogen uptake in pure form to a certain degree. However, in the planned net zero future, the factory gate price for green hydrogen will always be lower than that of the following net zero e-fuels that rely on green hydrogen.

[32] https://www.iba.aero/insight/rolls-royce-commits-to-100-sustainable-aviation-fuel-capability-for-civil-aircraft-engines/

6 EXPLOITATION POTENTIAL

KEY POINTS

- Cenex attempted to estimate the number of vehicles in NI. Of the data available, most vehicles in NI are road vehicles, with 81% of the market being cars, 10% vans and 2% trucks. Agriculture, mining, and quarrying vehicles account for a few percent of the vehicle stock. The number of aviation and marine vehicles are unknown.
- UK industry fuel use data was adjusted to estimate NI fuel demand. This showed that the current potential total market for waste agri-fuels in the NI transport sector is estimated at 15,500 GWh with a market value of around £1bln. Key transport market sectors are Aviation (46%), Road Transport (25%) and Maritime (10%).
- The total market size is expected to be similar by 2050. However, due to the shift to ZE drive trains and improvements in transport efficiency, the key markets in 2050 are estimated to be Aviation (58%), Maritime (16%) and Construction (12%).

Consideration for Further Work

- Refinement of fuel demand estimates through undertaking further research, determining low, medium and high scenarios.
- Estimation of a more focused market growth factor considering changes in each transport segment.
- There was little or no data available on the number and types of vehicles in the NI construction, mining, aviation and marine sectors. Further research and industry consultation should be undertaken to determine the make-up of these vehicles parcs in NI.

6.1 Vehicle Numbers in NI

Cenex estimated the number of vehicles in NI from publicly available information. Key data sources and confidence levels are shown in the table below.

	Reference and Comments	Confidence Level
Motorbike Car LGV	UK licencing data NI vehicle parc[33] split available[34]	High
Truck (Rigid) Truck (Artic)	UK licencing data[35] split by rigid/artic[36] modified by NI vehicle parc split[37].	Medium
Bus	NI Open data [38]	High
Train	The NI transport statistics report 2021 states there are two dedicated locomotives operating in Northern Ireland. However, this figure contradicts numbers reported by NI rail, who state that a fleet of 47 trains (and therefore a minimum of 47 propulsion units) are in operation. This discrepancy is due to the technical use of the term 'locomotive': The majority of the engines in the NI train fleet are multiple units where the powertrain is included in a compartment that can also transport passengers.	High
Tractors	Based on annual UK tractor sales with an estimated 20-year replacement cycle (assumes ten-year use across two owners in the UK).	Low
Mining, quarrying and Construction	Mining, construction, and quarrying numbers are based on global and regional plant equipment sales. [39, 40] This includes vehicles such as miniature diggers, 90-tonne road rollers, cranes, and static screens and crushers. Approximately 1 million such units are sold each year globally, with 160,000 unit sales in Europe. The mining and quarrying figures reported in Table 8 assume that NI contributed 0.2% (NI contribution of UK GDP) of these annual purchase figures in 2018 and that mining and construction equipment has a 20-year lifetime (assuming two owners each operating the equipment for ten years each). A similar logic is applied to the figures used in the construction sector.	Low
Marine	Not available	
Aviation		

[33] https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/812253/vehicle-licensing-statistics-january-to-march-2019.pdf
[34] https://www.economy-ni.gov.uk/publications/energy-northern-ireland-2020
[35] https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/812253/vehicle-licensing-statistics-january-to-march-2019.pdf
[36] *Table VEH0521 Vehicle licensing statistics data tables - GOV.UK (www.gov.uk)*
[37] https://www.economy-ni.gov.uk/publications/energy-northern-ireland-2020
[38] https://www.opendatani.gov.uk/dataset/licensed-bus-vehicles & Energy 2018
[39] *Eurostat (2022): Annual detailed enterprise statistics for industry (NACE Rev. 2, B-E)*
[40] *Statista (2022): Off-Highway Research; Statista estimates*

	Number of Vehicles	%
Motorbike	23,000	2%
Car	980,000	81%
LGV	120,000	10%
Truck (Rigid)	9,500	1%
Truck (Artic)	12,500	1%
Bus	3,400	0%
Trains	47	0%
Tractors	17,700	1%
Mining and Quarrying	6,200	1%
Construction (Tractors)	3,300	0%
Other	41,000	3%
Marine	Unknown	-
Aviation	Unknown	-
Total (known)	1,216,700	100%

23,000 980,000 120,00

9,500 12,500 3,400

47 17,700 6,200 3,30

41,000 1,216,700

6.2 Transport Fuel Demand in NI

The section above presents the number of vehicles in the NI fleet, where these can be reasonably inferred from available data. There is limited data on the types, duty cycles and fuel consumption of the NI vehicle parc.

To understand the potential Agri-fuels market, it is more accurate to look at the total fuel sales to the relevant industry sectors. The process undertaken by Cenex to estimate total Agri-fuel demand in NI is detailed below.

Establish Energy Supply Per Transport Sector in NI

Apply a Simple Factor for NI Economic Growth to estimate energy demand to 2050

Adjust Energy Demand per Vehicle Category based on Technoloy Roadmaps to represent potential market size for Agri-fuels

6.2.1 Energy Use Per Transport Sector

Cenex based its assessment of the transport sector energy use on the Office for National Statistics (ONS) data which lists total fuel use in the UK by industry sector. Relevant categories for Transport fuel use in the data set were:

- Agriculture, forestry and fishing
- Mining and quarrying
- Construction
- Transport and storage
- Aviation fuel (spirit and turbine fuel)
- Maritime bunkering (note: established from a different data source detailed below)

The data set presented a variety of fuel types, which were normalised to kWh of energy consumption for this report. The fuels reported in the data set and the method used to estimate the kWh and £ per kWh are discussed below.

6.2.1.1 Determining Energy Consumption and Market Value from the Fuel Use Data

The types of fuels assessed are described in the table below.

Fuel Oil (or Marine Fuel Oil)

Also known as heavy oil, marine fuel oil, marine gas oil, bunker oil and other names. There is a wide variety of fuel oils with different viscosities and chemical compositions. In this report, we will use the term Marine fuel Oil (MFO) and where possible, we will use data for "MFO-IFO380".

M FO-IFO380 is a medium-heavy fuel oil, widely available in the UK, and typically one of the lower-cost maritime fuels on the market[41]. As such, this can be considered a conservative estimate.

Gas Oil

Also known as red diesel, this is a reduced taxation fuel used in industrial applications such as agriculture, rail, heating, domestic electricity generation, ground maintenance, marine craft (excluding private pleasure craft in NI as of June 2022) and powering specialist machinery. Until April 2022, red diesel was also permitted in the construction industry and several other sectors.

This is no longer the case. Gas oil use is heavily influenced by a handful of sectors, with construction, storage (e.g., warehousing), manufacturing and mining and quarrying accounting for 84% of usage (prior to April 2022). Gas oil has the same chemical make-up as diesel, and therefore diesel energy consumption has been used.

Diesel Engine Road Vehicle (DERV)

DERV is diesel used to power road-going transport. For the purposes of this high-level market assessment, gas oil, diesel and petrol are treated as diesel. It should be noted that the prices used in this report for gas oil, diesel and petrol are all based on the wholesale price of diesel[42] in 2021. This includes UK fuel duty.

Kerosene (Aviation)

In this analysis, Kerosene denotes Aviation Spirit and Turbine Fuel and not fuel for home heating. Price estimates are based on the average wholesale price[43] in 2021

The table below shows the conversion factors used to present the fuel volumes reported to energy and use and market value. The values include UK fuel duty.

	Energy Density (kWh/litre)	Energy per Barrel (kWh)	Wholesale Price (£ per kWh)	Wholesale price (£ per GWh)
Diesel	10.9	1733.1	£0.09	£85,376
Kerosene	10.3	1637.7	£0.07	£65,105
MFO	11.9	1892.1	£0.03	£28,646

[41] https://shipandbunker.com/prices/av/global/av-glb-global-average-bunker-price#IFO380
[42] https://www.racfoundation.org/data/wholesale-fuel-prices-v-pump-prices-data
[43] https://www.iata.org/en/publications/economics/fuel-monitor/

6.2.1.2 Adjusting UK Fuel Use Data for NI

Within each category above, Cenex applied a NI conversion factor of 3.32%, which was determined by the GDP contribution to the UK. Exceptions to this were as follows:

- **Agriculture**, where it is estimated that 8% of UK agriculture is in the NI.
- **Aviation fuels**, Belfast airport and Belfast City airport have higher than average air freight and represent 3.62% of UK aviation fuel use.
- **Maritime** maritime bunker fuels have been extrapolated from a separate data set, UK Port Freight Statistics[44] where the author has assigned a proportion of UK national bunker fuels based on reported tonnes of shipping (this is not a direct representation of fuel use in NI ports). Based on the mass of shipping reported, NI is assumed to utilise 5.7% of total UK fuel bunkered (0.14 million tonnes of oil equivalent (M TOE), or 1,589 GWh.).

6.2.1.3 Energy Demand Forecast in Transport Segments

Using the analysis inputs described above, the table below shows base energy use in 2018 as per the data set; we have then applied an energy demand growth factor of 1.78% PA to estimate potential future growth[45].

GWh Fuel Demand by Transport Sector

	2018	2020	2030	2040	2050
Agriculture, forestry and fishing	759 (5%)	772	938	1,118	1,333
Mining and quarrying	657 (4%)	669	812	968	1,154
Construction	1,440 (9%)	1,465	1,778	2,121	2,529
Transport and storage	3,822 (25%)	3,890	4,721	5,630	6,714
Aviation fuel (spirit and turbine fuel)	6,921 (46%)	7,044	8,549	10,195	12,158
Maritime bunkering	1,589 (10%)	1,617	1,963	2,341	2,791
Total (GWh)	15,188 (100%)	15,458	18,761	22,373	26,680

The analysis above estimates the total addressable market for transport sectors is in the order of 15,000 GWh of energy demand in 2018. Based on the 1.2% growth rate discussed earlier, by 2050, a simplistic evaluation would estimate this figure at closer to 26,700 GWh.

The largest market segment is Aviation fuel (46%), followed by Transport (25%) and Maritime fuel (10%).

The next section of this report adjusts the demand estimates above in line with the expected demand for Agri-fuels.

[44] https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/1014546/port-freight-annual-statistics-2020.pdf

[45] *Whilst it is out of scope of this report to determine a specific economic growth rate for each of the transport segments, the average annual GDP change in NI of approximately 1.8% per year (based on figures from the twenty years covering 1999 to 2019) has been applied to the data. Further work is required to determine a more specific value considering wider factors such as transport mode shift, long-term impacts of recent events such as the war in Ukraine, Covid-19, Brexit, Net-Zero. It is worth noting that the NI economy (in terms of energy use and GDP) has yet to recover from the impact of the 2008 financial crisis fully. As such, there is an argument that the predictions in this report may overestimate the economy's growth rate.*

6.2.1.4 Estimation of Potential Agri-fuel Demand Forecast in Transport Segments

The total market estimates above present the energy demand for each NI transport segment.

Transport fuel segments are likely to undergo significant change between now and 2050. With the proposed ban on ICE engines for passenger vehicles (2030) and HGVs (2040), it is highly likely that liquid fuel markets for that sector will decline significantly. When looking to establish the potential demand for Agri-fuels within transport, we have removed energy demand from ZE technologies.

The table below summarises our adjustments to the transport segment energy demand by time-based on research in Section 2, Fuel and Transport Pathways.

Agriculture, forestry, and fishing

Includes energy efficiency will improve by 10% across the sector (through the improved engine designs and the adoption of electric and hybrid technologies).

A 20-year plant replacement cycle is assumed. ICE engines continuing to dominate the market for larger equipment until 2050.

Mining, quarrying and construction

Overall energy consumption efficiency improvement of 25% across the sector (through the improved engine designs and the adoption of electric and hybrid technologies).

A 10-year plant replacement cycle is assumed. ICE engines continuing to dominate the market for larger equipment until 2050.

Transport and storage

The currently planned UK ban on ICE (2030 for passenger cars, 2040 for HGV) will have a significant impact on the use of liquid and gaseous fuels in road transport.

This analysis assumes that by 2050 only one vehicle in 30 will still be powered through ICE technologies, based on approximated 'classic car' ownership rates.

Aviation fuel (spirit and turbine fuel)

Assumes a 25% efficiency improvement and the 30-year replacement cycle for jet engines. It should be noted that various aviation maps indicate a far higher rate of efficiency improvement over this period. However, the aviation sector lacks a clearly defined technology route.

Maritime bunkering

Assumes a 10% efficiency improvement and the 30-year replacement cycle for maritime propulsion. It should be noted that smaller vessels (under 500 tonnes) may be able to achieve significant levels of electrification. However, this will have little impact on the total energy consumption for shipping as a whole..

NI liquid fuels energy demand prediction (GWh, 1.8% growth adjusted for decline in liquid/gas fuel demand)

	2018		2020		2035		2050	
Agri, forestry and fishing	759	5%	722	5%	921	6%	1,200	8%
Mining and quarrying	657	4%	669	4%	665	4%	886	5%
Construction	1,440	9%	1,465	9%	1,456	9%	1,897	12%
Transport and storage	3,822	25%	3,890	25%	3,307	20%	181	1%
Aviation fuel	6,921	46%	7,044	46%	7,295	49%	9,118	58%
Maritime bunkering	1589	10%	1,617	10%	2,014	12%	2,512	16%
Total	15188	100%	15457	100%	16288	100%	15774	100%

NI addressable market value estimate (£, 1.8% growth adjusted for decline in liquid/gas fuel demand)

	2018	2020	2030	2040
Agri, forestry and fishing	£64,800,535	£65,951,516	£78,669,493	£102,446,993
Mining and quarrying	£56,103,361	£57,099,864	£56,759,086	£73,914,264
Construction	£122,913,471	£125,096,648	£124,350,058	£161,934,303
Transport and storage	£326,308,744	£332,104,609	£282,305,753	£15,491,915
Aviation fuel	£450,605,498	£458,609,110	£515,979,661	£593,657,368
Maritime bunkering	£45,518,400	£46,326,894	£57,689,225	£71,962,727
Total	£1,066,250,009	£1,085,188,640	£1,115,753,275	£1,019,407,570

The tables above show

- The current market for Agri-fuels in the NI transport sector is estimated at 15,500 GWh with a market value of £1 billion. Key transport market sectors are Aviation (46%), Road Transport (25%) and Maritime (10%).
- The market is still estimated to be 15,800 GWh with a market value of £1 billion in 2050. Due to the shift to ZE drive-trains and improvements in transport efficiency, the key markets in 2050 are Aviation (58%), Maritime (16%) and Construction (12%). The road transport demand for waste Agri-fuels will reduce significantly by 2050 due to the direct use of electricity and hydrogen in an electric vehicle, which took them out of the scope of this study.

7 SUPPORTING POLICY AND LEGISLATION

KEY POINTS

- Cenex undertook a high-level review of policy and legislation relative to the future use of Agri-fuels in future transport options.
- Policy and legislation were separated into those driving the **Supply Side** (fuel suppliers) for renewable fuels, and those driving the **Demand Side** (transport operators).
- Key fuel **Supply Side** policies include the ban on the internal combustion engine (ICE) in road transport which will reduce the demand for liquid and gaseous fuels. The Renewable Transport Fuel Obligation (RTFO) which sets a target for fuel supply to have an increasing amount of renewable content, and the expected SAF Mandate which would legislate an increase in the renewable content of aviation fuel.
- Key **Demand Side** (transport operator) policies legislate the monitoring of energy and emissions by large organisations but do not require emission reduction actions to be taken by transport operators.
- No strong policy legislation is yet in place for the decarbonisation of Marine, Agriculture, Mining and Construction Sectors.
- The Republic of Ireland has announced plans to increase the renewable content of motor fuels and develop a CNG refuelling next work. These present a local market and opportunity for NI Agri-fuels.

7.1 NI & Republic of Island Targets

7.1.1 Northern Ireland

Northern Ireland (NI) is expected to achieve an 82% reduction in greenhouse gas emissions by 2050. In 2020, the UK DfT started developing policy proposals and coordinated plans for decarbonising with the Decarbonising Transport: Setting the Challenge report.

The NI climate change bill proposes a net zero carbon, climate resilient and environmentally sustainable economy by the year 2045 as a legally binding commitment. The Transport Strategy for NI is reported to be outdated, and a new local Transport Strategy is expected by the end of 2022/23.

7.1.2 Republic of Ireland

The Republic of Ireland is committed to achieving net zero by 2050, with a planned trajectory to reduce emissions in all sectors in-line with the net zero targets. This equates to a 7% annual average reduction in greenhouse gas emissions between 2021 and 2030. The Government published its Climate Action Plan in June 2019. The Climate Action Plan identifies how Ireland will achieve its 2030 targets for greenhouse gas emissions in a manner consistent with a trajectory to achieve net zero emissions.

Key plans relevant to this study are 1) Increase the renewable biofuel content of motor fuels underpinned by the biofuel's obligation scheme. 2) Develop the CNG fuelling network to support the uptake of CNG vehicles. These present a local opportunity and market for a drop in biofuels.

7.2 Legislation Affecting the Supply of Renewable Fuels

7.2.1 ICE Ban

The UK government has set the target of ending all new ICE passenger car and light commercial vehicle (LCV) sales in the UK by 2035 and all ICE HGV sales by 2040. At the time of writing, there are no plans to ban ICE engines in agriculture, mining, construction, aviation, or maritime sectors. However, with the collapse of the global passenger and LCV ICE supply chains likely, other ICE-based technologies may experience some degree of supply chain disruption.

To date, agriculture, mining, construction, aviation and maritime have largely committed to fuel efficiency improvements (hybridisation, improved engine efficiency, operational improvements) and the use of biofuels. However, zero emissions trials in all sectors are underway and should be monitored closely.

7.2.2 Renewable Transport Fuel Obligation (RTFO)

The primary mechanism used by the UK government to drive the supply of sustainable fuels in the transport system is the RTFO. The RTFO has been in existence since 2008. The RTFO was developed to implement the transport elements of the EU Renewable Energy Directive (RED). RTFO registration is obligatory for any organisation supplying 450,000 litres of fuel or more. Under the RTFO, UK suppliers of transport fuel must be able to show that a percentage of the fuel they supply comes from renewable and sustainable sources. Renewable Transport Fuel Certificates (RTFCs) are awarded to suppliers whose renewable fuel meets sustainability criteria.

RTFO mechanisms include:

- **Crop Cap** which limits the amount that can be sourced from specified crops (prevents ILUC).
- **Developmental Fuel Targets** which provide double credit for fuels sourced from sources specified as desirable (e.g., biomethane from anaerobic digestion).
- The **Specified Amount** is the sum of the development fuel target and the main renewable fuels obligation. This increases each year.
- Fuel suppliers must prove they have sufficient RTFCs in a given year. If not, they must pay a buy-out price.
- The RTFO is guaranteed to 2032

7.2.3 SAF Mandate

The UK Government has consulted on the introduction of a SAF mandate that is world-leading and as ambitious as possible. To that end, the consultation sets out a number of potential SAF uptake scenarios, up to 10% SAF by 2030 and up to 75% SAF by 2050.

A long-term objective is to generate demand for SAF, provide an incentive to SAF producers (in the form of a tradable credit) and signal to investors the vital role the Government believes the technology will play in the UK.

7.2.4 Motor Fuel GHG Emissions Reporting Regulations

Motor Fuel (road vehicle and mobile machinery) Green House Gas Emissions Reporting regulations came into force in 2012. The reporting regulations initially required annual reporting by fuel suppliers on the amount, energy content and GHG emissions of relevant fuels. From 2019 onwards, an additional requirement for suppliers to achieve a minimum 6% reduction in lifecycle GHG emissions in 2020 (88.45 gCO_2e/MJ) relative to an EU average in 2010 (94.1 gCO_2e/MJ) as part of the EU Fuel Quality Directive. Similar to the RTFO, suppliers are awarded credits for fuels meeting sustainability/GHG criteria. The credits awarded to fuels include:

- Sustainable renewable fuels.
- Electricity in road transport.
- Relatively low carbon fuels such as LPG and CNG.
- 6% target was removed in 2021, although the reporting obligation continues.

7.3 Legislation Affecting the Use of Renewable Fuels by Transport Operators

7.3.1 Companies Act (2006)

In 2013 the Companies Act (2006) was amended to require all UK quoted companies, and those companies with more than 500 employees, to measure and report Scope 1 (direct emissions from transport owned/operated by the company) and 2 (indirect emissions which include electricity purchases) GHG emissions. Global emissions must be reported, not only those of UK origin. This brought the UK into alignment with the European directive 2014/95/EU.

7.3.2 Energy Savings Opportunity Scheme (ESOS)

ESOS requires large enterprises to do an energy audit (including transport) by an external verified ESOS assessor. An ESOS assessment benchmarks the energy use of an organisation and highlights energy reduction options. The UK Government established ESOS to implement the EU Energy Efficiency Directive. The scheme applies throughout the UK, and audits are required every 4-years. Fines for non-compliance are up to £50,000. However, other than reporting, there is no obligation for companies to reduce their emissions.

8 ECONOMICS OF RENEWABLE FUELS

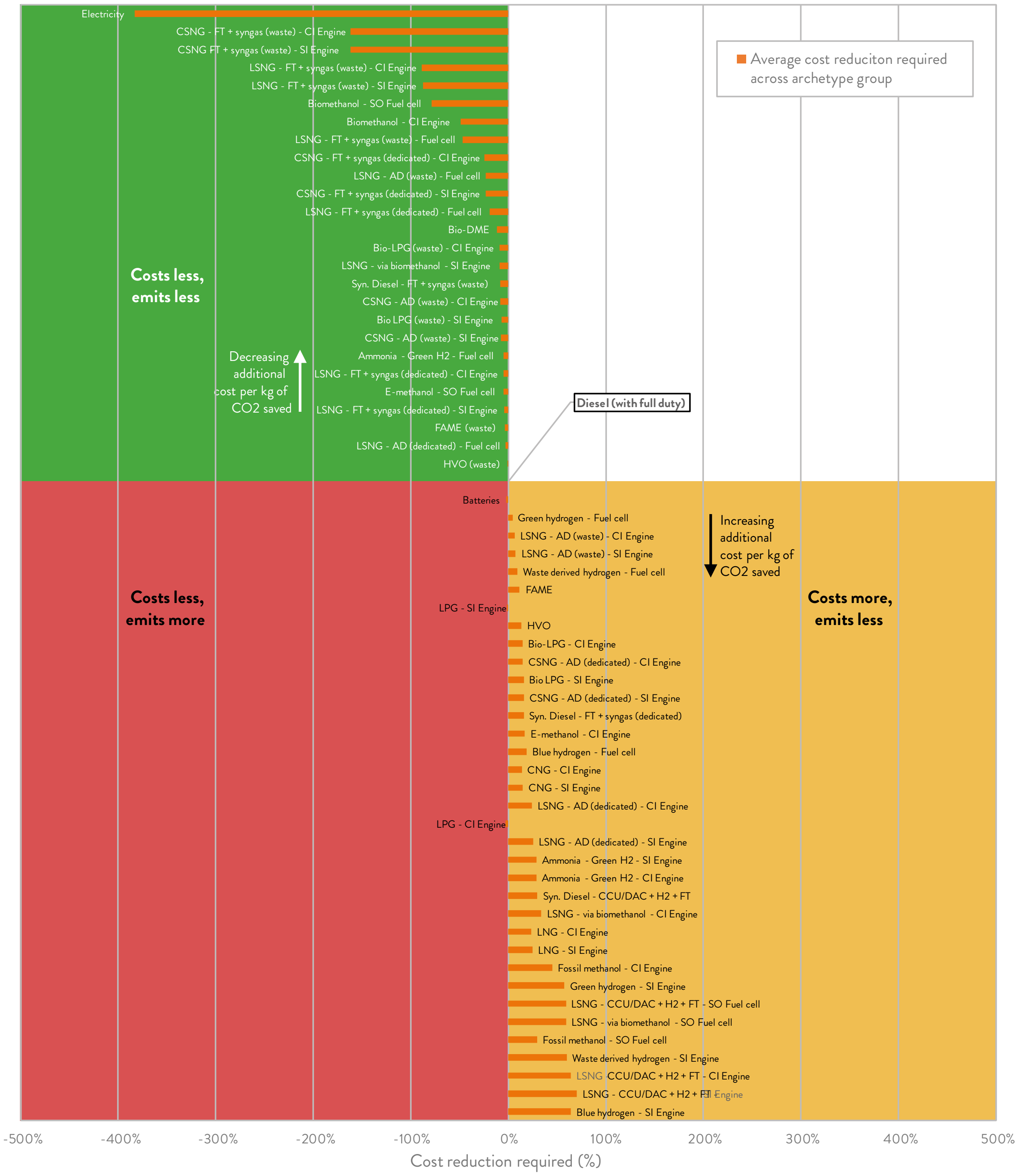
KEY POINTS

- A study undertaken by E4Tech and Cenex in 2020 looked at the future economics of alternative fuel supplies for the off-road equipment sector.
- The study compared fuels on a total cost of ownership basis which included fuel supply and use costs for an operator. The study considered fuels on a NOAK (nth of a kind) basis, which assumes costs of a mass market and mature fuel supply system.
- The study highlighted Bio-methanol, Bio-LPG, E-methanol, Bio-methanol, Ammonia, FAME, Synthetic CNG and LNG could all potentially be cost competitive against the current cost of diesel fuel supply.

Potential Future Work

- A NI specific future fuel economic study should be developed considering NI unique logistical and infrastructure considerations.

While it is outside of the scope of this study to undertake a financial analysis of the different future fuel supply chains, a study undertaken by E4Tech and Cenex in 2020 highlights a number of future fuel options as economic. The study considered both fuel supply routes and final energy conversion on a vehicle. It applied a cost reduction factor to represent a mature technology. The study looked at the following technologies for final energy conversion.



Based on the above analysis, the projected cost parity (or better) as technologies improve to the 'Nth of a kind iteration' (Nth of a kind assumes technological advancements occur along a predicted path and that fully developed technologies become available as a commercial product).

The list of fuels below are projected to achieve cost parity (or better) and have fewer emissions than diesel ICE powertrains.

Battery electric	Bio-methanol - ICE	BioLPG – ICE	E-methanol in ICE
LSNG - ICE	Bio-methanol - FC	Ammonia – FC	FAME (from waste) – ICE
CSNG - ICE	Bio DME - ICE	Syn gas ICE	LSNG - FC
HVO (waste)			

9 COMPARISON OF TRANSPORT FUELS

KEY POINTS

- A RAG matrix was used to summarises the potential performance in the 2035 and 2050 timeframe of the key renewable fuels.
- In the period to 2035 there is likely to be good demand for drop in diesel replacement fuels across Agriculture, Mining, Maritime, Construction and Road transport as these sectors look to decarbonise but await maturity of 2050 net zero fuel options. Demand for bio-methane would be limited by the availability of suitable ICE vehicles. There will be growing demand for SAF due to a mandate for increased use of the fuel which is expected to be announced by the UK government over the next year.
- In the period of 2035 to 2050 there is likely to be a significant decline in demand from the Road transport sector and also a decline from Agriculture, Mining and Construction sectors as these sectors are able to turn to more ZE options. There is a strong demand from Maritime and the Aviation sector where long distance transportation requires the energy density from liquid fuels. The RTFO legislation ceases in 2032 and is likely to refocus incentives for renewable fuels at hard to electrify areas such as heavy industry and long-haul shipping and aviation.

This analysis summarises the performance of key renewable fuels that could be manufactured from Agri-fuel waste against economic, legislative, export potential and NI market size. The assessment summarises potential performance in the 2035 and 2050 timeframe based on the research undertaken in this study.

9.1 RAG Matrix Key

The key for the RAG matrix and explanatory notes are below.

	Industry profitability	Industry profitability	Supporting legislation	Export potential	NI Market Size per year
Red	Low margin industries (typically >2.5%)	More expensive than diesel (> 25%)	No supporting legislation planned	NI Market only	<£49 m
Amber	Medium margin industries (2.6 to 5%)	Similar to diesel (+/- 25%). Or performance variable	Supporting legislation under development	UK and Ireland only	£50 – 500 m
Green	High-margin industries (>5%)	Cheaper than diesel (> 25%)	Legislation in place	International trading likely	>£500 m

Industry Profitability

Higher profit-making industries may be less sensitive to price variability in new cleaner renewable fuels. Where possible, each fuel has been rated in accordance with the industry mean profitability. For agricultural purposes, an average 10-year profit margin of 5% has been assumed: this is approximately half of the value reported in US farm data, which is typically considered a world leader in profitable farming practice.

Construction profit margins are typically in the order of 1.5%[46]. Mining profit margins are typically in the order of 17%. As an aggregated sector (Mining, construction and agriculture), the estimated weighted profitability for the sector is estimated at 6.0%.

Fuel Economic Performance

The economic performance of the final energy cost [fuel supply chain + final energy conversion to mechanical power on a vehicle] relative to diesel has been determined from the E4Tech/Cenex red diesel report referenced in Section 5. Both the 2035 and 2050 scenarios represent the 'nth of a kind result' reported by the study.

The nth of a kind scenario represents the cost of fuel supply in a mature mass market scenario. The reference report states many production pathways and end mechanical conversion technologies. Therefore, where fuel performance varies significantly across different types, these have been labelled as amber.

Supporting Legislation

Any known or expected key legislation is highlighted.

[46] https://www.theconstructionindex.co.uk/news/view/construction-pre-tax-margins-average-15

Export Potential

Export potential is assessed based on the extent to which potential fuels are traded as international commodities.

NI Market Size

The market size has been determined from the analysis presented in Section 3 of this report. The applicable transport market segments are highlighted in the tables.

9.2 2035 Fuel Potential

	Industry profitability	Fuel economic performance	Supporting legislation	Export potential	NI Market Size per year
Bio-methane	Average UK Road haulier[47]	Biomethane from AD	RTFO in place to 2032	Traded in 2022	Growing demand but market penetration limited by suitable ICE vehicles
Bio-methanol			IMO and DNV developing standards	Traded in 2022	Maritime
Ammonia		From Green H2	IMO and DNV developing standards	Traded in 2022	Maritime
Renewable diesels	Agriculture, mining, and construction		Legislation in place in 2022	Traded in 2022	Agriculture, Mining, Maritime, Construction, Transport
e-diesel				Growing demand but market penetration limited by cost factors	Agriculture, Mining, Maritime, Construction, Transport
SAF			SAF mandate likely to be in place	Growing demand but market penetration limited by engine replacement cycles	NI Aviation sector demand

In the period to 2035, there is likely to be good demand for drop-in diesel replacement fuels across Agriculture, Mining, Maritime, Construction and Road transport as these sectors look to decarbonise but await maturity of 2050 net zero fuel options. Demand for bio-methane would be limited by the availability of suitable ICE vehicles.

There will be growing demand for SAF due to a mandate for increased use of the fuel, which is expected to be announced by the UK government over the next year.

[47] UK: Leading road hauliers profit margin 2008-2018 | Statista

9.3 2050 Fuel Potential

	Industry profitability	Fuel economic performance	Supporting legislation	Export potential	NI Market Size per year
Bio-methane	Average UK Road haulier[47]	Biomethane from AD	RTFO legislation in place until 2032 only	Traded in 2022	Diminishing demand due to ICE ban in road transport ICE vehicles
Bio-methanol			IMO and DNV developing standards	Traded in 2022	Maritime
Ammonia		From Green H2	IMO and DNV developing standards	Traded in 2022	Maritime
Renewable diesels	Agriculture, mining, and construction			Traded in 2022	Agriculture, Mining, Maritime, Construction, Transport
e-diesel				Growing demand but market penetration limited by cost factors	Agriculture, Mining, Maritime, Construction, Transport
SAF			SAF mandate likely to be in place	Widespread use in aviation sector likely	NI Aviation sector demand

In the period of 2035 to 2050, there is likely to be a significant decline in demand from the Road transport sector, and also a decline from Agriculture, Mining and Construction sectors as these sectors are able to turn to more ZE options. There is a strong demand from Maritime and the Aviation sector where long-distance transportation requires the energy density from liquid fuels.

The RTFO legislation ceases in 2032 and is likely to refocus incentives for renewable fuels at hard to electrify areas such as heavy industry and long-haul shipping and aviation.

10 DISCUSSION

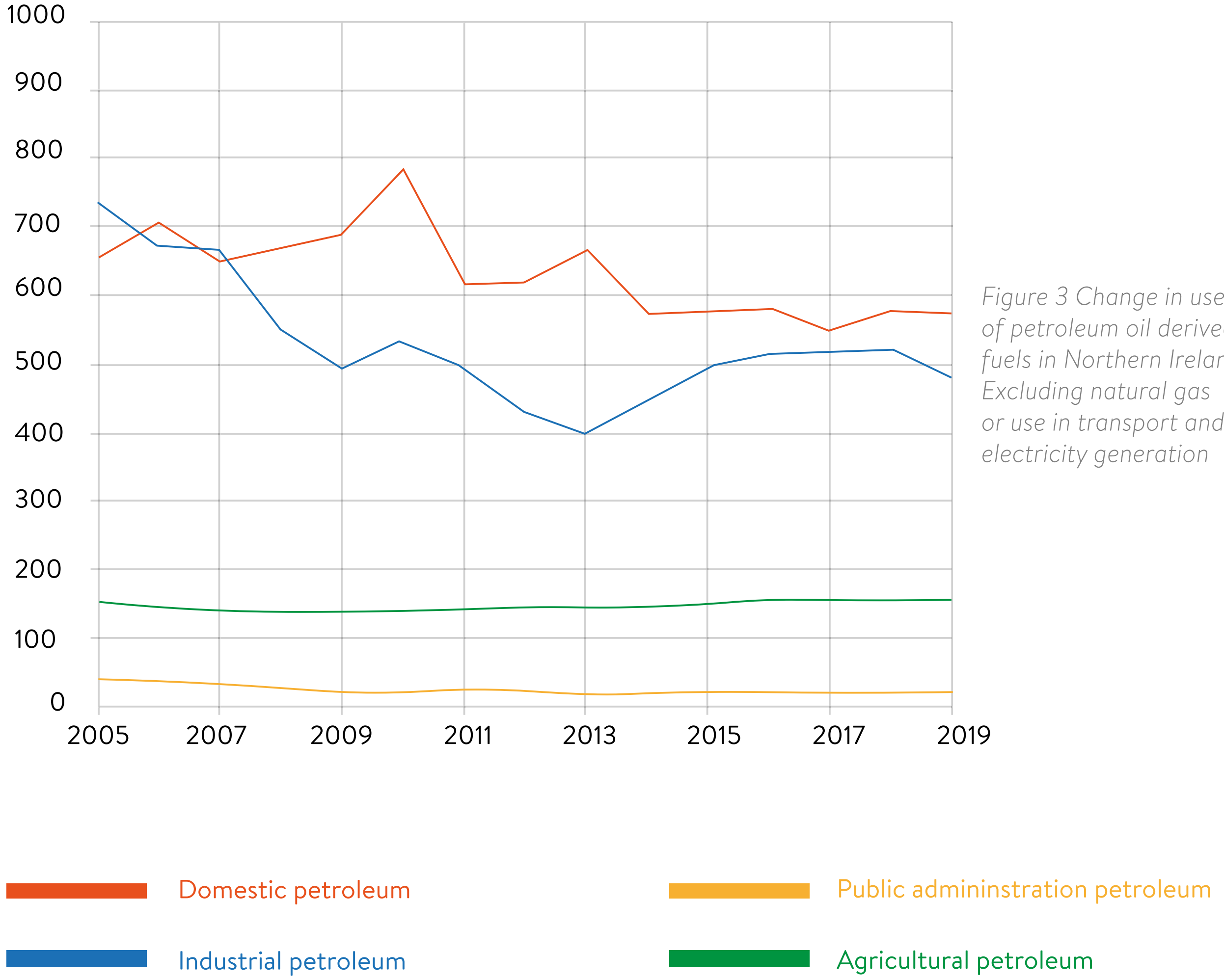


Figure 3 Change in use of petroleum oil derived fuels in Northern Ireland. Excluding natural gas or use in transport and electricity generation

The above shows the use of petroleum-derived fuels within Northern Ireland, excluding transport fuels, use for power generation and not including natural gas usage[48] . Domestic use for heating and overall industrial use has dropped by c100ktoe and c300ktoe respectively since 2005. This is mainly due to the roll-out of the gas network across the region (99 ktoe increase in gas use between 2015[49] and 2019) and improvements in the energy efficiency of homes and businesses.

Agricultural use has stayed relatively constant despite the switch in other sectors to natural gas and initiatives such as the renewable heat incentive (RHI). Farming is mainly a rural occupation, so the connection to the gas grid is assumed to be less likely. A switch to biomass burning (under RHI) or biogas from anaerobic digestion over the period 2005-2019 is likely offset by the increase in agricultural production of housed livestock needing heating (increases of 40.7% of poultry and 66% of pigs). It is worth noting that from across all sectors, energy from biomass and waste increased from 103.9 ktoe in 2005 to 575.9 ktoe in 2019.

[48] https://www.gov.uk/government/collections/sub-national-consumption-of-other-fuels

[49] 2015 is the first year gas consumption data is available for NI. See: https://www.gov.uk/government/statistics/total-final-energy-consumption-at-regional-and-local-authority-level-2005-to-2019

It is important to note that energy from biomass and waste in 2019 (575.9 ktoe) is almost equivalent to that from natural gas at 608.2 ktoe. To date, only a small amount of the potential for biogenic carbon-derived fuels has been realised. As previously described, recent research[50] shows that utilising a mix of farm slurries and excess silage to generate biomethane could substitute for up to 80% of the natural gas presently consumed in Northern Ireland. It is, however, noted that the majority of NI homes are not on the gas grid, and therefore overall substitution is lower in NI relative to the rest of the UK.

Biogenic carbon from wastewater sludge, farm and forestry wastes, food waste, as well as specially grown bioenergy crops (e.g., hemp, miscanthus, willow) or wood potentially offers the most economic and achievable source of synthetic fuels. However, the quantities of carbon drawn down into biogenic carbon and available for conversion to synthetic fuels is unlikely to meet energy demands in a one-to-one swap for fossil fuels. As shown in section 4.3, the above 80% substitution of biogas in the existing gas grid drops to 26% when considering energy demand across power, transport, and heat. As such new industries such as algae biorefineries, vertical farming for carbon sequestration[51] or the development of large-scale seaweed farms (e.g., kelp) may be able to provide sufficient additional biogenic carbon, but the likelihood is that other synthetic e-fuels such as hydrogen, ammonia or e-methanol will be required in large volumes.

In 2019, Northern Ireland consumed 2479 ktoe of petroleum-based fuels, 608 ktoe of natural gas and 176 ktoe of coal – a total of 3263 ktoe. Assuming a complete displacement of fossil fuels and, as a rough estimate, assuming double the amount of biomass is required to produce one tonne of oil equivalent fuel, then over 6.5 million tonnes of biomass will be required to replace oil and gas-derived fuels over and above existing biomass collection and usage levels. A complete displacement of fossil fuels by biogenic carbon source fuel requires a factor of five or more increase on the 2019 biomass and waste figure. In reality, greater energy efficiency such as insulating homes and electrification of transport and some heating will make a significant dent in the quantity of biogenic carbon needed, but this still represents a factor of three (or more) increase in the volume of all forms of biomass that would be needed.

In a previous report[52], a mean simulated Net Primary Productivity (NPP) value for GB[53] of 0.608 kgC m^{-2} $year^{-1}$ across all vegetation types and a NI land area of 14,130 km^2 was used to estimate NI's annual carbon capture as 8.6 Mt. Satellite observation data[54] of the NPP gives a slightly lower value of 8.4 Mt of Carbon adsorbed across NI. These figures will include food production and carbon necessary for ecosystem consumers and consider all land to be productive. Collection and utilisation efficiency of the accessible, land-based, biogenic carbon makes it extremely unlikely that an additional 2 to 3 Mt of biomass can be collected, even allowing for the addition of imported biogenic carbon such as food and animal feed.

Additional biogenic carbon could come via special designed vertical farms – for example, Carbotura[51] has proposed a hemp-growing vertical farm capable of sequestering 55kt CO_2 per year, but this would come at substantial CAPEX and operational costs. A more economic option could be seaweed-based aquaculture which has been demonstrated to have a high potential to remove CO_2 while offering routes to generate fuels and increase fish and other seafood production[55]. Differing sea conditions and temperatures affect the choice of seaweed and growth rate. For a general comparison to the sea round NI, inshore kelp (Saccharina latissimi) production in Scotland has been estimated to yield up to 220 tonnes/hectare, whereas in Norway[57] production volumes have been modelled to yield between 150 and 200 tonnes per hectare for offshore farms.

Scaling up the results for NI implies that to generate 1 Mt of wet biomass then, this would require c5,000 hectares or 50 km^2 of NI's marine area of approximately 6000 km^2. This is not insignificant considering marine protected areas and that access needs to be maintained for existing activities such as fishing, transport and leisure as well as future marine energy projects. However, given the options available, especially when considering the replacement of chemicals produced from oil, it will probably become necessary to consider significant aquaculture activities. Already there is a growing industry for food and biochemical production from various seaweeds, as detailed in a recent (2021) report[58] from Crown Estate Scotland on the economics of kelp cultivation. This report also indicated that biofuel production from kelp was not yet commercially viable. However, recent events in Ukraine and the resultant doubling of oil prices will make biofuel production much more attractive.

[50] *DOI:10.1016/j.renene.2022.06.115*
[51] *See for example https://www.carbotura.com/*
[52] *Carbon Capture, Utilisation and Storage Potential in Northern Ireland (2021). See: https://www.brydencentre.com/ccus*
[53] *DOI: 10.1088/1748-9326/ab492b*
[54] *MODIS/Terra Earth Observing System satellite: MOD17A3HGF Version 6 data for the year 2018*
[55] *DOI: 10.1016/j.psep.2012.10.008*
[56] *DOI: 10.1016/j.aquaculture.2012.03.019*
[57] *DOI: 10.3389/fmars.2018.00529*
[58] *https://www.crownestatescotland.com/resources/documents/economic-feasibility-study-on-seaweed*

10.1 Expected conversion technologies

A range of technologies has been highlighted within this report, including biochemical, thermal and chemical processing techniques. Only a broad overview of these has been presented with a focus on technologies which are expected to produce the greatest alignment with the NI economy and resources. Assuming that NI will continue to have a significant and growing agri-food sector, anaerobic digestion was considered one of the core technologies. At present, this is extensively used for agricultural waste in NI but has yet to be applied extensively to other waste streams such as sludge from wastewater treatment or domestic green and food waste, and there is significant further potential for bio and e-methane production. While fermentation technologies such as ethanol production are established alternatives, the energy productivity per hectare is reduced when compared to grasses used for silage.

Complementary to AD is pyrolysis (heating of feedstock <500 °C in an inert atmosphere) or gasification (heating of feedstock to typically >700 °C in an inert atmosphere), which can be applied to digestate as well as other biogenic waste streams such as forestry trimmings and chicken litter or fossil-fuel derived waste (plastics, waste oil). These processes can be used to produce a synthetic gas or syngas (typically a mix of CO, CO_2, methane, hydrogen, and other compounds) plus oils and biochar (for pyrolysis). Syngas can be used directly in gas-fired engines, but post-processing can yield pure streams of hydrogen, methane as well as methanol. The Fischer-Tropsch process, using syngas as the feedstock, can produce a range of drop-in liquid hydrocarbon fuels and oils and other oxygenates. Other well-established catalytic processes include methanol and, through further processing, DME, ethylene, propylene and even plastics. Basically, once clean synthesis gas is available, then this can serve as a platform chemical for a larger biorefinery. There are other technologies, such as Aqueous Phase Reforming, which can produce syngas which has the advantage of operating in water at a lower temperature than pyrolysis or gasification. This also has the advantage of being more closely aligned in terms of processing conditions allowing for higher system efficiencies when coupling endo and exothermic reactions. However, feedstock prices and research to develop low-cost and robust catalysts are needed.

Although pyrolysis and gasification are simple in concept, they work best with a consistent and uniform biogenic or other waste feedstock such that the process can be optimised for the desired end-products. Seasonal variations in moisture, constitution or mixed waste feedstocks can cause difficulties, especially where syngas is not being used to supply a gas engine. In NI, there are several waste streams of carbonaceous materials such as solid digestate (from AD), forestry waste and other waste wood, sewage sludge and municipal waste. Applying lessons from the NI Water treatment industry, these streams could be aggregated to provide a more consistent feedstock for conversion within NI for a range of end-uses.

It is noted in the report that biogenic feedstocks, including digestate, wood, agri-food wastes etc., are effectively oxygen-rich and hydrogen deficient. While oxygen can help improve engine efficiency, its presence lowers the energy density. Hence reacting the feedstock with hydrogen to produce water is desirable. Within the report, we have shown how biogenic carbon can be upgraded using green hydrogen, thereby acting as a hydrogen storage vector. While many of the reactions produce waste heat which is not passed to the final product, the same is true of compression technologies. In both cases, it is recommended that this waste heat is used as effectively as possible in order to improve overall energy efficiencies.

Waste vegetable and plant-based oils are an additional category of biogenic materials which can be directly converted to HVO using hydrogen and either used directly as a fuel or blended with fossil diesel to make HVO Renewable diesel. This is already on sale in NI. HVO can also be used as an almost drop-in replacement for kerosene (heating oil). The regional availability of waste oils is limited and insufficient to meet the potential demand for HVO. Virgin oil production could be more significant but is not a waste product, and even at scale in NI is unlikely to be a realistic long-term option. Also of note is that the majority of plant-based oils are imported from tropical regions, and production increases have been a major cause of deforestation across the globe.

An alternative to biomass conversion is the conversion of CO_2 to fuels. Within the report, AD was used as a readily available source of high concentration CO_2. There are, however, other sources, and across NI, there are only six significant[59] emitters of CO_2. Around 83% of CO_2 across the region is emitted from small domestic and medium-scale sources (including transport). While this pattern will change significantly with the energy transition, these existing sources (power generation, cement, and chemicals) represent an opportunity to deploy different technologies to capture and upgrade the CO_2 to a useful e-fuel.

The impact on the efficiency of this is yet to be fully investigated. Like direct air capture technology, there is a significant cost and energy associated with Carbon capture. This would need to be added to the cost of hydrogen production and subsequent conversion when compared to the utilisation of more concentrated streams. Earlier calculations have shown that the use of hydrogen to upgrade CO_2 from an extended AD network would require in excess of 1.8 GW of offshore wind, which is larger than that which is feasible in NI.

While the focus of this study is on biogenic waste and re-purposing emitted CO_2, it is worth noting that there is significant potential to assess the future role of different land-based energy crops. In the longer-term biogenic feedstocks based on seaweed, aquaculture could also be an attractive option for NI, considering the length of the coastline compared to the landmass.

10.2 Technologies under development

Under controlled conditions in which the nutrients, water, warmth, and CO_2 are supplied in the correct proportions, microalgae can fix CO_2 at rates up to x50 higher than soil-grown plants[60]. Several varieties exist, and cultivating these provides opportunities to exploit a wide range of products[61] , including:

- Biodiesel and other biofuels
- Food for fish, animals, and humans
- Fertiliser
- Bioplastics
- Pharmaceutical precursors and other chemicals

Around the world, companies and research groups are developing and commercialising technology for the growth, harvesting and processing of algae and bacteria. Production of fuels has been a focus but to date has been uneconomic compared to alternative sources due to yields and the relatively expensive extraction process from algae cells. This is why most biorefineries have been concentrating on higher value products. However, increases in fuel prices make algae sourced biofuels more competitive and a combination of factors such as access to free nutrients, heat, and CO_2 together with low-cost renewable electricity for lighting plus utilisation of post-processing waste streams could make this more economic.

In an NI context, such an approach makes most sense as part of hub of green activities, where waste heat, CO_2 and cheap, off-grid or curtailed power is readily available. A synfuel plant, AD, CHP, biomass boiler or many other industries could readily be partnered synergistically with an algae-based biorefinery.

[60] DOI: 10.1021/bp070371k
[61] DOI: 10.3389/fmars.2019.00029

Appendix A

Below is a list of roadmaps consulted during the research for Section 5 of this report.

- https://www.apcuk.co.uk/app/uploads/2021/09/https___www.apcuk_.co_.uk_app_uploads_2021_02_Exec-summary-Product-Roadmap-HGV-and-Off-highway-final.pdf
- CarbonTrust - Roadmap for the Decarbonisation of the European Recreational Marine Craft Sector
- IMO initial GHG strategy - https://www.imo.org/en/MediaCentre/HotTopics/Pages/Reducing-greenhouse-gas-emissions-from-ships.aspx
- Ten Year Network development plan - European Network of Transmission System
- Operators for Electricity 2021 - https://eepublicdownloads.blob.core.windows.net/public-cdn-container/tyndp-documents/TYNDP2020/FINAL/entso-e_TYNDP2020_IoSN_Main-Report_2108.pdf"
- EIRGRID TES 2019 - http://www.eirgridgroup.com/site-files/library/EirGrid/EirGrid-TES-2019-Report.pdf
- United states aviation climate action plan 2021 - https://www.faa.gov/sites/faa.gov/files/2021-11/Aviation_Climate_Action_Plan.pdf
- IRENA - Global Energy Transformation: A Roadmap to 2050 https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2018/Apr/IRENA_Report_GET_2018.pdf
- UK Gov - energy white paper - https://www.gov.uk/government/publications/energy-white-paper-powering-our-net-zero-future/energy-white-paper-powering-our-net-zero-future-accessible-html-version
- Network Rail TRACTION DECARBONISATION NETWORK STRATEGY (2020) - https://www.networkrail.co.uk/wp-content/uploads/2020/09/Traction-Decarbonisation-Network-Strategy-Interim-Programme-Business-Case.pdf
- DfT: Decarbonising Britain, a better greener Britain (2021): https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/1009448/decarbonising-transport-a-better-greener-britain.pdf
- DECARBONISATION ROAD-MAP: A PATH TO NET ZERO: 2020 sustainable aviation
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