Decarbonising ships, planes and trucks: An analysis of suitable low-carbon fuels for the maritime, aviation and haulage sectors

Nathan Gray a,b , Shane McDonagh a,b , Richard O’Shea a,b , Beatrice Smyth c , Jerry D Murphy a,b ,∗

a MaREI Centre, Environmental Research Institute, University College Cork, Ireland
b School of Engineering, University College Cork, Ireland
c School of Mechanical and Aerospace Engineering, Queen’s University Belfast, Belfast, UK

A R T I C L E   I N F O

Keywords:
Transport
Haulage
Shipping
Aviation
Alternative fuels
Low carbon

A B S T R A C T

The high environmental impacts of transport mean that there is an increasing interest in utilising low-carbon alternative energy carriers and powertrains within the sector. While electricity has been mooted as the energy carrier of choice for passenger vehicles, as the mass and range of the vehicle increases, electrification becomes more difficult. This paper reviews the shipping, aviation and haulage sectors, and a range of low-carbon energy carriers (electricity, biofuels, hydrogen, and electrofuels) that can be used to decarbonise them. Energy carriers were assessed based on their energy density, specific energy, cost, lifecycle greenhouse gas emissions, and land-use. In terms of haulage, current battery electric vehicles may be technically feasible, however the specific energy of current battery technology reduces the payload capacity and range when compared to diesel. To alleviate these issues, biomethane represents a mature technology with potential co-benefits, while hydrogen is close to competitiveness but requires significant infrastructure. Energy density issues preclude the use of batteries in shipping which requires energy dense liquids or compressed gaseous fuels that allow for retrofits/current hull designs, with methanol being particularly appropriate here. Future shipping may be achieved with ammonia or hydrogen, but hull design will need to be changed significantly. Regulations and aircraft design mean that commercial aviation is dependent on drop-in jet fuels for the foreseeable future, with power-to-liquid fuels being deemed the most suitable option due to the scales required. Fuel costs and a lack of refuelling infrastructure were identified as key barriers facing the uptake of alternatives, with policy and financial incentives required to encourage the uptake of low-carbon fuels.

1. Introduction

To limit global temperature rise to 1.5 °C, anthropogenic net greenhouse gas (GHG) emissions must approach zero by 2050 [1]. Decarbonisation pathways for power generation [2], light-duty transport [3], and domestic heating/cooling [4] are relatively well established. However, emissions from heavy industry, agriculture, and heavy-duty transport (trucks, buses, maritime shipping, and aviation) are more difficult to eliminate [5].

Transport (including aviation) is the largest source of GHG emissions in the EU (27%) and the only sector where current emissions are greater than in 1990 [6]. While cars alone contribute the most (43.9% of transport emissions), heavy-duty transport has a combined greater impact at 46.2% [6]. Electric vehicles (EVs) represent a maturing technology suitable for passenger or light-duty vehicles but as the range and mass of the vehicles increase, electrification becomes increasingly difficult. Therefore, alternative fuels and powertrains are required to achieve deep decarbonisation of heavy-duty transport. The demand for heavy-duty transport has been shown to grow as a nation’s economy develops [7,8]. Demand side management and modal shift from high carbon intensity modes of transport, such as aviation, to lower carbon intensity modes of transport, such as shipping or rail will be necessary to reduce GHG emissions [9]. Additionally, the decarbonisation of the transport sector as a whole will affect efforts to reduce emissions from heavy-duty transport. As electric vehicles replace internal combustion engine vehicles in the passenger car sector, the overall demand for fossil fuels in...
the transport sector will fall. The leftover fossil fuel demand within the heavy-duty transport sector can then be met in a sustainable manner using alternative fuels and powertrains.

The recast EU Renewable Energy Directive (RED) drives the uptake of alternative fuels within the EU, requiring that a minimum of 14% of the energy in transport comes from renewable sources by 2030 [10]. The recast RED places greater emphasis on advanced fuels and sets in place a move away from food crop-based biofuels, capping their contribution at 7%. This means that there is a de facto target of 7% of the energy in transport to come from advanced fuels by 2030, which includes renewable electricity, renewable fuels of non-biological origin, and advanced biofuels produced from waste and residue feedstocks, listed in Annex IX of the recast RED [10].

Currently road haulage [11], shipping [12] and aviation [13] are all reliant on liquid or gaseous fuels produced from fossil resources (Fig. 1). Alternative fuels can be roughly grouped into two categories: those that utilise existing combustion engine technology and infrastructure, and those that use electric motors powered either by either fuel cells or batteries (Fig. 1). These fuels can come in the form of biofuels [14] or electrofuels [15] (liquid or gaseous), hydrogen or electricity (Fig. 1). Heavy-duty transportation has constraints on cargo space and payload that mean fuels with high energy density (MJ/m$^3$) and specific energy (MJ/kg) are required for economic operation [5]. Despite often being grouped together shipping, aviation and haulage each presents unique challenges for decarbonisation. It is clear that energy-dense renewable liquid (biofuels, cryogenic hydrogen or synthetic fuels) or gaseous (compressed hydrogen or biomethane) transport fuels produced via pathways as shown in Fig. 1 are required where electrification is not yet feasible. Over recent years, there has been increasing interest in alternative fuels for the heavy-duty transport sector, as can be seen in Table 1.

Previous literature has examined alternative fuels for maritime [28,29], aviation [30,31] and haulage [32,33] individually. However, there is a scarcity of literature outlining the operational requirements of each sector and hence, the alternative energy carriers and powertrains that are applicable and why. In a fast moving state-of-the-art, this paper addresses that gap by aiming to provide a comprehensive overview of the heavy-duty transport sector and outline a broad perspective on the decarbonisation pathways available. Firstly, the current state-of-the-art for each sector will be broadly reviewed and applicable alternative fuels and powertrains selected (Step 1 and Step 2, Fig. 2). The selected fuels will then be assessed based on their energy density (Step 4, Fig. 2), cost (Step 5, Fig. 2), lifecycle GHG emissions (Step 6, Fig. 2) and land area usage (Step 7, Fig. 2). Novel case studies and calculations are presented in the paper highlighting the mass and volume of alternative energy carriers needed to power each mode of transport in order to illustrate the technical feasibility of each energy carrier. It is difficult to analyse renewable energy systems in a generic manner on a world-wide basis. This is particularly true for bioenergy systems with great differences between tropical countries such as Brazil and temperate oceanic climates such as Japan. This can be compounded by issues such as population densities, arable land area per capita, climatic conditions and energy infrastructure. Ireland, as an island nation with a temperate oceanic climate, a relatively dispersed population and poor rail connectivity, is representative of countries that will be heavily reliant on sea and air transport as well as road haulage for many years to come. It was therefore decided to use Ireland as a case study for the land area required to produce alternative fuels at the scales required. Furthermore, wider implications such as infrastructure costs and efficiencies are brought into the discussion to give a comprehensive overview of low-carbon fuels available to reduce emissions from the road haulage, shipping and aviation sectors (Step 8, Fig. 2). To the best of the authors’ knowledge this is the first review to provide such a broad review of the potential pathways to decarbonise the heavy-duty transport sector.

2. Sectoral analysis

2.1. Maritime shipping

2.1.1. Sectoral overview and classification of shipping vessels

The maritime shipping sector carries approximately 80% of global trade by volume, and 70% by value [34–36]. There are around 90,000 merchant ships in service globally, and significant variation across the fleet exists (Table 2), with vessels typically categorised by purpose (goods, passengers, services), size, and carrying capacity [37]. Vessels used for different purposes have differing requirements in terms of fuel type propulsion [34].

General cargo ships, passenger ships, and work vessels are the most common ship type by number globally, with most of these being small and medium sized vessels used for shorter shipping distances. Conversely, large and very large ships make up only 20% of the global fleet by number, but account for 82% of the fleet’s gross tonnage [37]. Bulk carriers, tankers and container ships make up the majority of large and very large vessels, carrying over 85% of shipping trade and accounting for 70% of the shipping sectors fuel demand [34].

The route models also affect vessel and therefore fuel choice. Larger modern vessels are able to take advantage of economies of scale and are typically used on longer international routes (deep-sea shipping), with smaller often older vessels dominating passenger and coastal/inland
Table 1
State of the art in alternative fuels for heavy-duty transport.

| Project Title       | Project Aims                                                                 | Applicable Sectors | Reference |
|---------------------|------------------------------------------------------------------------------|--------------------|-----------|
| ENABLEH2            | To demonstrate the feasibility of utilising liquid hydrogen for civil aviation| Aviation           | [16]      |
| JETSCREEN           | To provide aviation fuel producers with a streamlined screening tool to help evaluate the chances of success in the approval process| Aviation           | [16]      |
| Bio4A               | To scale up the industrial production and the market uptake of sustainable aviation fuels, made from residual lipids. | Aviation           | [17]      |
| FlexJET             | To develop a scalable and less capital-intensive process for the production of sustainable jet fuel from a diverse range of feedstocks (waste vegetable oils and organic solid waste) | Aviation           | [18]      |
| REWOFUEL            | To demonstrate the potential to produce high-quality bio-jet fuel from residual soft woods | Aviation           | [19]      |
| Westküste 100       | To produce synthetic jet fuel by combining hydrogen produced from electrolysis and CO₂ captured from cement production | Aviation           | [20]      |
| FLAGSHIPS           | To raise the readiness of hydrogen powered waterborne transport, through the deployment of two commercially operated zero-emission hydrogen fuel cell vessels in France and Norway | Maritime           | [21]      |
| ShipFC              | To demonstrate the feasibility of ammonia as a zero-carbon marine fuel by retrofitting the vessel Viking Energy with a 2MW ammonia fuel cell | Maritime           | [22]      |
| HySHIP              | To demonstrate the feasibility of hydrogen as a marine fuel through the construction of a roll-on/roll-off vessel powered by liquid hydrogen | Maritime           | [23]      |
| Hyundai H₂ Xcient HGV | The delivery of hydrogen powered heavy goods vehicles for use in Switzerland | Road haulage       | [9]       |
| Daimler GenH2       | The development of a 40-t hydrogen powered HGV with a claimed range of up to 1000 km | Road haulage       | [24]      |
| Sunfire PtL         | Demonstration Power-to-Liquid plant, combining hydrogen produced from renewable electricity and captured CO₂ to produce liquid fuels | Road haulage       | [25]      |
| Kopernikus P2X      | The development of Power-to-X technologies, including for the production of liquid fuels | Road haulage       | [26]      |
| Carbon Recycling International | Commercial electrofuel plant, producing methanol from hydrogen produced form geothermal electricity and captured CO₂ | Road haulage       | [27]      |

Fig. 2. Flow diagram outlining methodology used.
cargo routes (short-sea shipping) [34]. Liners and tankers (regular passenger/routes) with fixed schedules may have set contracts with fuel suppliers at specific ports [34]. Conversely, charter services have no fixed route and must deal with irregular fuelling patterns at different ports with fuel price and supply uncertainty. Thus, distance from regular routes to refuelling infrastructure becomes a consideration. With several key routes (Europe, North America and East Asia) experiencing high volumes of traffic, it may be possible to reach a large proportion of the global fleet with relatively limited infrastructure [38].

The average lifespan of a shipping vessel is 30 years, and up to 40 years given correct operation and maintenance [34], with most of today’s fleet less than 15 years old (Fig. 3) [37,39]. Large and very large ships are typically newer as the ability to economically manufacture them is also relatively new (Fig. 3) [37]. Thus, decisions made today regarding new vessel construction must be compliant with a low carbon energy system, as these vessels are likely to still be in service by 2050. The potential to retrofit current vessels with low carbon propulsion technologies will also play a key role in reducing emissions from the shipping sector, but challenges remain in convincing ship owners and operators to invest in greener technologies [39]. Therefore, a mix of “drop-in” fuels and advanced low carbon systems are likely to be required to meet any reductions targets.

2.1.2. Emissions from shipping

The International Maritime Organisation (IMO) estimate that shipping emits 2.8% of annual global emissions or 1036 Mt of CO_2 p.a, predominantly from container ships, bulk carriers and oil tankers (Fig. 4) that travel internationally [40].

The emissions from individual vessels (CO_2, SO_4, NO_x and methane) vary by fuel and efficiency [36] however, the shipping sector as a whole emits approximately 1.4 Mt of particulate matter (PM), ~15% of global NO_x emissions, and ~13% of SO_4 emissions p.a [41]. These emissions are damaging to human health and the global environment [42]. Of the nearly 300 Mt of fuel consumed by the sector in 2015, 72% came from typically high sulphur content residual fuels such as heavy fuel oil (HFO), 26% from more refined distillate fuels such as marine diesel oil (MDO) and 2% from liquified natural gas (LNG) [12].

The International Convention for the Prevention of Pollution from Ships (MARPOL) through the IMO and under the United Nations regulates shipping emissions [43]. The IMO predict growth in GHG emissions of 50–250% by 2050 under business as usual scenarios [40]. However, in 2018 they agreed to reduce GHG emissions by 50% by 2050 compared to 2008 through more efficient ships, operational and logistical improvements, and the use of alternative fuels [36]. The Energy Efficiency Design Index (EEDI) is currently the only enforceable carbon emissions policy in place to reduce CO_2 emissions from shipping, setting minimum carbon efficiencies for newly built ships [36,44]. The entire global shipping fleet is not expected to be EEDI compliant until at least 2040 and hence EEDI alone is insufficient for the IMO target; low carbon fuels are therefore required [36].

At the same time, from the 1st of January 2020, the sulphur content of maritime fuel is also to be limited to 0.5%, or 0.1% in IMO enforced Emissions Control Areas (ECAs) [34]. Current ECAs include the North Sea, the Baltic Sea and North America and the Caribbean, and with plans to integrate Japan and the Mediterranean Sea as future ECAs, a large volume of maritime traffic is covered by ECA regulations [34]. The introduction of ECA regulations means HFO is no longer compliant unless it undergoes intensive desulphurisation prior to use [43,45]. Alternatively, vessels can be fitted with on board sulphur scrubbers or switch to low-sulphur fuels (such as LNG, biofuels or hydrogen) [45]. Permissible levels of NO_x emissions, dictated by vessel age and maximum en-

![Fig. 3. Global fleet by ship size and age.](image1)

![Fig. 4. CO2 emissions from international shipping by ship type.](image2)

Table 2

| Vessel Size | % of Global Fleet | By Gross Tonnage | Estimated Dead Weight Tonnage (DWT) | Example Vessel Types |
|-------------|------------------|-----------------|-------------------------------------|----------------------|
| Small       | Less than 500    | 37              | 1                                   | Less than 1000       |
| Medium      | 500 – 25,000     | 43              | 17                                  | 1000 – 5000          |
| Large       | 25,000 – 60,000  | 13              | 34                                  | 5000 – 60,000        |
| Very Large  | Greater than 60,000 | 7          | 48                                  | Greater than 60,000  |

1 Defined as a function of the total enclosed volume of a vessel, from keel to funnel.  
2 Defined as the total mass a ship can safely carry, including for cargo, fuel, provisions, passengers and crew but not including the mass of the ship itself.
gine operating speed, are also regulated by the IMO [34]. While SOx emissions originate from sulphur content in the fuel, NOx emissions are caused either by nitrogen in the fuel (problematic for certain biofuels) or by reactions with nitrogen in the air during combustion (problematic with higher temperature, more efficient engines) [46,47]. Methods of reducing NOx emissions involve altering the combustion process through technologies such as exhaust gas recirculation (EGR) or exhaust gas aftertreatment such as selective catalytic reduction (SCR) [34].

2.1.3. Current marine propulsion technologies

The shipping sector is mostly powered using heavy-duty diesel engines similar but larger and more efficient than their land-based counterparts [34,48,49]. Two-stroke engines operate at low speed (~350 rpm), offer high thermal efficiencies (~50%), allow direct shaft connection (minimising transmissions losses), and tolerate high viscosity fuels (such as HFO) due to their heating chambers [34,48]. However, they are much larger than four-stroke engines and are mainly used to propel large deepsea vessels designed to travel at constant speeds and loads. The more compact four-stroke engines are generally used in small to medium-sized vessels used for coastal/inland shipping and typically require more refined, less viscous distillate fuels (such as MDO) [34,49].

LNG has been used to power tankers since the 1970s, using boil-off gas from the LNG tank in traditional boiler/steam turbine systems [46,47]. More recently, the use of LNG as a fuel in other vessel types (such as ferries and offshore support vessels) has been developed in order to meet the sulphur limits in ECAs [46,47,50,51]. LNG contains little sulphur, reducing SOx emissions by up to 90%, NOx emissions by up to 80% (lower peak temperature of combustion), with significant PM emissions reductions too compared to HFO [46]. The use of LNG can also offer GHG reductions of up to 20% however, the level of GHG emissions from LNG ships is highly dependent on the level of methane (GWP100 of 25–28) slip both onboard and in the fuel supply chain [46,50]. Alvarez et al. indicate that current methane leakage from natural gas infrastructure is higher than previously thought, meaning that any climate benefit seen from lower CO2 emissions during combustion could be cancelled out by upstream methane leakage [52]. LNG is generally cheaper than liquid fossil fuels, although newly constructed LNG ships are 20–25% more expensive than oil-fuelled vessels and retrofitting vessels is more expensive still [36,51]. The cost of adding LNG facilities to ports is also significant [36]. Burel et al. found that as Roll-on/Roll-off vessels and tankers spend most of their time sailing within ECAs they are the most appropriate candidates for LNG as a maritime fuel [46].

2.1.4. Future marine propulsion technologies

Ideal shipping fuels should display a particular set of characteristics, including:

- High energy density (MJ/L) and specific energy (MJ/kg) to minimise fuel volume and mass and allow for long-distance travel
- Produce low levels of local emissions (SOx, NOx and PM), to ensure compliance with IMO ECA regulations
- Low energy costs (€/MWh), to ensure cost competitiveness with low-quality residual fossil fuels
- Low lifecycle GHG emissions (gCO2e/MJ), to meet the IMO goal of reducing emissions from shipping by 50% by 2050
- Scalability, to ensure that large volumes of fuel are available at the quantities required of the shipping sector
- Widespread bunkering infrastructure, to ensure vessels are able to refuel at ports around the world
- Compatibility with existing infrastructure, to allow for decarbonisation of current vessels and future potential retrofit projects

While the use of LNG as a marine fuel may offer benefits, such as reduced air pollutants compared to residual fuels (HFO), its use is not enough to reduce carbon emissions in line with the IMO goal of 50% by 2050. The climate sustainability of LNG powered vessels can be improved upon by utilising liquified biomethane, which can display significantly less lifecycle GHG emissions than LNG, depending on the source of the biomethane. Additionally, low-carbon electricity can be used to produce methane via power-to-gas (PtG) technologies, which can then be liquified for use in the maritime sector.

State-of-the-art multifuel diesel engines (high temperature and pressure injection) which allows both traditional fuels and fuels with low cetane numbers (such as ethanol and methanol) to be used in the Diesel cycle are currently under development [34,36,44,53]. The marine engine manufacturer Wärtsilä has developed an engine for the Stena Germanica, the world’s first methanol powered ferry, where methanol is injected into the engine cylinder and ignited with a small amount of pilot fuel (such as diesel) [36,53]. Furthermore, there is the potential for the use of diesel-like biofuels, such as hydrotreated vegetable oils (HVO), fatty-acid methyl esters (FAME), and Fischer-Tropsch diesel to be used in current marine engines with little to no engine or bunkering modifications [34,36,44]. However, while blend walls limit the fractions of FAME biodiesel that can be used [34].

Hydrogen which is stored onboard as a compressed gas (700 bar) or as a liquid (cryogenic, ~252 °C) and used in fuel cells has been mooted as an efficient way to produce electricity for propulsion and auxiliary electricity demand, with water as the only direct emission (Table 1) [36,54]. The energy density of both compressed and cryogenic hydrogen is substantially less than HFO [36], meaning substantial cargo carrying capacity is sacrificed for energy storage in a retrofit, and new builds would require substantial redesigning. Similar energy density and recharging time constraints likely preclude the use of battery-electric powertrains in shipping without substantial improvements in battery technology [5].

Lack of infrastructure at ports is another barrier to the uptake of hydrogen. Potential solutions to this is the construction of hydrogen infrastructure on specific point-to-point routes between highly developed ports (such as Singapore and Rotterdam) or in a small geographic area (such as Irish Sea ferry crossings) [36]. An interesting option for the shipping sector is the use of ammonia as an alternative fuel [54,55]. Ammonia liquefies much more readily than hydrogen (~33 °C at atmospheric pressure) and can be combusted directly in a multifuel engine in the presence of a pilot fuel or used as a hydrogen carrier for fuel cell applications [54,55]. Additionally, as ammonia is already a commodity that is traded globally, some of the infrastructure needed to produce it as a fuel already exists [55]. However, hydrogen has advantages over ammonia in terms of production efficiency (~70% [56] from electrolysis vs. ~50% for ammonia from electrolysis and synthesis [55]) and utilisation efficiency (fuel cell is 60% [57] vs. dual fuel of 40% [58]).

Nuclear fuel can offer shipping a low-carbon, high air quality, and long range option, with many military vessels utilising small onboard nuclear reactors for power generation [36,44]. However, nuclear material is a highly sensitive geopolitical issue. Furthermore, many ports around the world have banned nuclear vessels from docking over concerns surrounding safety, meaning nuclear vessels are currently restricted in what routes they can sail culminating in low potential for large-scale deployment before 2050 [36].

Another option to consider for future shipping is the potential to retrofit existing vessels with low-carbon technologies. DNV GL identifies ships between 8 – 19 years old as strong candidates for retrofitting [59]. The retrofitting process involves replacing the vessels existing propulsion system with low-carbon alternatives. The majority of current retrofit activities in the shipping sector have focussed on the installation of advanced multifuel engines [60] capable of operating using alternative fuels such as LNG or methanol [59]. Fuels such as hydrogen and ammonia are still emerging technologies, and as such are not yet widely available for retrofits. The main advantages of retrofitting are environmental, offering reductions in GHG emissions as well as reduction in air pollution in line with IMO ECA regulations. Challenges faced by retrofit projects include capital costs (e.g. new propulsion system), operating costs (e.g. increased fuel costs), access to fuel and time out of service for the retrofit to take place [59]. Deniz and Zincir explore the costs associated with retrofits, reporting that capital investment for
Table 3
Aircraft classification.

| Aircraft type   | % of global fleet by number [62] | Purpose                                                                 | Passengers | Example variants |
|-----------------|----------------------------------|-------------------------------------------------------------------------|------------|-----------------|
| Narrowbody      | 58                               | Single aisle aircraft traditionally used on short/medium-haul routes (2-6 h) | 120–240    | Airbus A319/Boeing 737 |
| Widebody        | 20                               | Large aircraft traditionally used on high demand long-haul routes (>6 h)  | >250       | Airbus A330/Boeing 747 |
| Regional Jet    | 12.6                             | Small aircraft suited for short-haul operations (1-2 h)                  | 50–125     | Embraer E-Jet    |
| Turboprop       | 9.4                              | Suited for short-haul flights only (<1 h)                               | 25–90      | Bombardier Q400  |

A methanol system is 350 €/kW while investment in a LNG system is 1000 €/kW [41]. As methanol is a liquid at room temperature and pressure, it can be stored in the vessels existing fuel tank. The main costs for the methanol system are engine conversion costs and engine room safety modifications. As LNG must be stored under cryogenic conditions, the majority of the capital costs for the LNG system are associated with the LNG storage tanks and its safety systems. As costs are of great importance to vessel operators, it would appear that methanol is particularly appropriate for retrosfits.

2.2. Aviation

2.2.1. Sector overview and classification of aircraft

As of 2019 aviation was one of the fastest-growing sources of energy related emissions and the most climate intensive mode of transport [8,61], with the global aircraft fleet expected to grow from approximately 27,000 in 2019 to 39,000 by 2030 [62] (not accounting for the effects of the COVID-19 pandemic). Meanwhile, aircraft manufacturers are delivering only incremental and declining efficiency gains. It is clear that operational and logistical improvements along with sustainable fuels are needed to achieve deep decarbonisation of the aviation sector [8].

Aircraft used in the aviation sector can be divided into different classifications depending on size and use (Table 3). Typically, twin-engine narrowbody aircraft are utilised on domestic/transcontinental routes though there is great interest in using them on transatlantic/intercontinental routes too due to their higher fuel efficiency, meaning their share of the fleet is likely to increase [63]. Widebody aircraft are the most expensive variant of aircraft and an increase in “point-to-point” rather than the traditional “hub and spoke” model of flying has led to a decrease in demand for this type of aircraft [63].

The operational lifespan of an aircraft is determined in terms of the number of pressurisation cycles (flights) it has undergone [64]. Typically, as short-haul aircraft can make several flights per day they reach the allowable number of pressurisation cycles faster than long haul aircraft. In general terms, a typical commercial aircraft is expected to be in operation for 25–30 years [63]. The current average age of the global aircraft fleet is 11.3 years old and is predicted to drop to 10.7 years by 2029 [62]. As such many aircraft built today may still be in service by 2050.

2.2.2. Emissions from aviation

Aviation emits roughly 2% of global emissions or 900 Mt CO₂ e p.a [13,65]. While aviation emits significant amounts of CO₂ from combustion, it is also responsible for considerable amounts of non-CO₂ warming effects [66,67]. Condensation or vapour trails produced at high altitudes lead to net increased warming and the emission of NOₓ into the upper atmosphere stimulates the production of ozone, which also causes short term warming effects [66,67]. Therefore, it is estimated that aviation is responsible for an estimated 4.9% of anthropogenic warming [8]. These non-CO₂ warming effects will persist when combustion is used, although evidence suggests that condensation trail formation may be reduced by the use of synthetic fuels [25].

Since 2012 aviation emissions have been included in the EU emissions trading scheme (EU ETS) and in 2016 the International Civil Aviation Organisation (ICAO) introduced the Carbon Offsetting and Reduction Scheme for International Aviation (CORSIA) [68,69]. Both are market-based instruments designed to reduce aviation CO₂ emissions but with fundamental differences in their operation.

The EU ETS legislation was initially designed to apply to emissions from all flights to, from, and within the European Economic Area (EEA), however, in 2013 it was decided to temporarily limit the coverage of the EU ETS to flights within the EEA only [69]. This so-called “stop the clock” decision was only supposed to be in effect until 2016 but in light of the CORSIA agreement the EU has decided to maintain the geographic scope of the ETS to intra-EEA flights from 2017 onwards [69]. The EU ETS operates as a cap-and-trade system where emissions are capped at 95% of the average historical aviation emissions from the years 2004–2006, with the cap being incrementally reduced over time to further reduce emissions; airlines exceeding this cap are required to purchase allowances including from other sectors [69]. Work by Scheelhaase et al. indicates that the EU ETS in its current form can potentially reduce global aviation emissions by 4% by 2036 (although there may be issues of carbon leakage), whereas a “full scope” EU ETS with no geographic exemptions has the potential to reduce global CO₂ emissions from passenger aviation by 16% [69].

Unlike the EU ETS, CORSIA acts as an offset scheme with no emissions cap, but all (or a share of) the emissions must be compensated for by purchasing a tradeable carbon credit or by investing in projects that deliver measurable CO₂ reductions in sectors where emissions reductions are cheaper [69]. CORSIA was designed to enable carbon-neutral growth of the aviation sector, by requiring that any emissions above a baseline year must be offset (initially decided as the mean of 2019 and 2020 emissions although the impact of the COVID-19 pandemic must presumably now be accounted for) [69]. The CORSIA scheme is due to start in 2021 and requires carbon offsets to be purchased for all routes between participating states. Currently, 71 states have joined the CORSIA scheme, accounting for 87.7% of global tonne-kilometres [69]. Modelling by Scheelhaase et al. indicates that emissions reductions due to the CORSIA scheme will start rather small with a 1.4% reduction in 2021, however as the aviation sector grows larger reductions will be seen with 18% reductions predicted by 2039 compared with business as usual scenarios [69].

2.2.3. Jet fuel specifications

Jet fuel is specifically made for use in aircraft with the main chemical components being alkanes, isoalkanes, cycloalkanes and aromatic compounds [30]. The high hydrogen to carbon ratio of the alkanes ensures the fuel has the required energy density, while cycloalkanes help to reduce the freezing point and the presence of aromatics improves the lubricity of the fuel and also ensures seals and O-rings function as designed to prevent fuel leakage [30]. The two most common grades of jet fuel are Jet A and Jet A-1, the main difference being the freezing point (−40 °C for Jet A vs. −47 °C for Jet A-1) [70]. Additionally, a grade of jet fuel known as Jet B is used in cold weather climates such as northern Canada and Alaska, where enhanced cold-weather performance is required [71].

Due to the increased interest in alternative aviation fuels, a new specification (ASTM D7566) was created to outline the standards required for jet fuels containing synthetic hydrocarbons [72]. If a synthetic jet fuel meets the requirements of ASTM D7566, it is considered to be a Jet A/A-1 compliant fuel [72]. There are currently five ASTM approved pathways for producing alternative jet fuels, four of which produce a fuel composed exclusively of paraffinic hydrocarbons known as synthet-
sized paraffinic kerosene (SPK) [73]. SPK fuels do not contain any aromatic compounds, which are required in jet fuel to ensure seal swell and prevent fuel leakage. For this reason, along with other safety concerns surrounding alternative jet fuels, SPK fuels must be blended with conventional jet fuel up to 50% depending on the conversion route [72]. While there are current trials of alternate fuels blended up to 100%, substantial testing is required to prove their safety and reliability to gain full certification [74]. The fifth route is the production of SPK and aromatics (SPK/A). Although SPK/A in principle constitutes a fully synthetic jet fuel, it is still required to be blended to a limit of 50% with petroleum jet fuel, as the ASTM are currently reluctant to give full approval to synthetic fuels, which presents a significant barrier to full decarbonisation of the sector [72,73]. The ASTM approved pathways for alternative jet fuel are [72,73]:

- Hydroprocessed esters and fatty acids (HEFA-SPK), from vegetable oils and animal fats, up to 50% blended approved
- Fisher-Tropsch synthesis (FT-SPK and FT-SPK/A), through catalytic conversion of syngas, up to 50% blended approved
- Alcohol-to-Jet (ATJ-SPK), also called alcohol oligomerisation, up to 50% blended approved
- Synthetic Isoparaffins (SIP-SPK), from hydroprocessed fermented carbohydrates, only up to 10% blended approved as the process only produces a single compound (farnesane)

Approval of jet fuels produced via the Fischer-Tropsch pathway is not restricted to certain feedstocks. This means that Fischer-Tropsch fuels produced via the power-to-liquid concept are ASTM approved. The same cannot be said for power-to-liquid jet fuels produced via the methanol-to-gasoline (MIG) process developed by Mobil, where ASTM approval is still pending [75]. Gaining certification for use in aviation is a significant barrier for novel fuels as the ASTM require up to 235,000 US gallons to be tested, which is a prohibitive amount of fuel to produce for research and development purposes [76]. The EU JETSSCREEN (Table 1) project aims to provide aviation fuel producers and jet engine manufacturers with a streamlined screening tool to help evaluate the chances of success in the approval process. The screening process uses low-cost small scale experimental and model-based testing to assess the properties of the alternative fuel prior to the lengthy and costly approval process [77].

2.2.4. Future aircraft propulsion technologies

Fuels for use in the aviation sector must display a particular set of properties, including [78]:

- High energy density (MJ/m³), to allow long-range flight
- High specific energy (MJ/kg), to decrease take-off weight and improve fuel efficiency
- High flash point (the temperature above which the fuel produces a vapour which can be ignited), to ensure safe operation
- Low freezing point and low viscosity in cold temperatures, to facilitate safe operation at cruising altitudes
- High thermal stability, prevents the chemical decomposition of the fuel within the gas turbine engine
- Good lubrication properties, to ensure the proper functioning of fuel pumps
- Sufficient aromatic compounds, to ensure correct O-ring seal and prevent fuel leakage

The aviation sector is uniquely dependent on gas-turbine engines and jet fuel for propulsion. All-electric aircraft are currently under development and show potential for use on short-range flights. Research has shown that in order to electrify a typical twin-engine narrowbody aircraft (such as the Airbus A320 or Boeing 737) with a range of 600 miles, 800 Wh/kg of specific energy is required from the battery pack which is four to five times the specific energy of current state-of-the-art battery technology [79]. The use of cryogenic hydrogen is in the research and development process (Table 1) but, similar to the electification of aircraft, is not expected to be a viable commercial option until later in the century [31,55]. The low energy density of alcohols combined with their incompatibility with today’s gas-turbine engines, currently make them unsuitable for the aviation sector [78]. Given the long operating life of commercial aircraft, the size of the global fleet and the lack of alternative aircraft propulsion technologies in the near to medium term, it is clear that in order to reduce emissions from the aviation sector, synthetic “drop-in” fuels are required.

2.3. Haulage

2.3.1. Sector overview and classification of haulage vehicles

This sector encompasses all activities associated with the movement of goods by road. Demand for haulage (freight) is a key indicator of the economic development of a region. For example, the road haulage sector grew by more than 30-fold in China between 1975 and 2015 [7]. Haulage is a significant consumer of fossil fuels, accounting for approximately 20% of total global oil demand, consuming 17 million barrels per day (Mb/d) [7,11]. Under a “business as usual” scenario, this is predicted to rise to 22 Mb/d by 2050 [11]. Therefore, there is significant need for logistical improvements and to transition the road freight sector to higher efficiency, low-carbon fuels in order to reduce both the energy demand and CO₂ emissions.

A wide variety of vehicles are used in the sector (Table 4). The function of these trucks varies depending on their size, carrying capacity and horsepower as well as on regional factors such as geography, local infrastructure, and the economic development of a region.

While LGVs, which are typically used for “last-mile” deliveries and urban logistics, dominate the global haulage fleet by number, HGVs account for a disproportionate share of vehicle activity despite lower stock numbers, due to typically higher annual mileage [11].

2.3.2. Emissions from haulage

As of 2015, road freight vehicles were responsible for 2600 Mt of CO₂e emissions, or approximately 7% of global emissions [11]. HGVs and MGVs account for 65% and 33% of road freight emissions growth since 2000 respectively due to their greater annual mileage (>100,000 km/year) and higher emissions per kilometre (1080 gCO₂/km for HGVs vs. 260 gCO₂/km for LGVs), with diesel making up 84% of all oil based products used in the sector [11]. Petrol use is rare due to the lower efficiency and is reserved for smaller LGVs [11]. Similar to both aviation and shipping, haulage is responsible for PM and NOₓ emissions. However, emissions from haulage are much more damaging to human health than emissions from aviation or shipping, which typically occur well away from population centres [82].

As part of the measures to reduce air pollution from haulage vehicles, emissions standards (such as Euro VI regulations) have been put in place to limit emissions of NOₓ, PM along with other pollutants such as unburned hydrocarbons [83]. For certification purposes, heavy goods vehicles (HGVs) must demonstrate on an engine test bed that they are able to comply with the relevant Euro VI emissions regulations. The introduction of these improved air quality standards means that GHG emissions from new haulage vehicles can be reduced from increased use of biofuels (renewable diesels) without significantly compromising air quality.

The Euro VI regulations do not directly address CO₂ emissions from HGVs, however legislation adopted by the EU in 2019 requires newly registered HGVs to offer CO₂ reductions of 15% from 2025 onwards and 30% from 2030 onwards, compared with the average HGV carbon intensity in 2019 [84]. Additionally, the regulation includes an incentive mechanism to encourage uptake of both zero-emissions (zero tailpipe emissions) and low-emission (carbon intensity less than half the average) HGVs [84].

2.3.3. Current haulage propulsion technologies

The haulage sector is currently powered almost entirely by diesel fuel in compression ignition engines, accounting for almost half of global
diesel demand [11]. The diesel used can be blended with biofuels (potentially up to 100%) to achieve emissions reductions but given the demand, complete replacement would be difficult [11]. Natural gas is less carbon intensive than diesel per MJ but supplies just 1.2% of haulage energy demand, primarily in dual-fuel compression ignition engines operating on either diesel or compressed/liquefied natural gas (CNG or LNG) [11]. However, work by Langshaw et al. indicates that spark-ignition LNG HGVs are 18% less energy efficient on a MJ/km basis than their diesel counterparts, which leads to an increase in well-to-wheel GHG emissions of 7% [85]. To address this issue, compressed or liquefied renewable gas can be used in CNG or LNG powered trucks to provide GHG emissions reductions similar to the use of renewable diesel, along with significantly reduced local emissions.

The use of battery electric LGVs and MGVs, such as the Nissan e-NV200 [86] or the Tesla semi-truck [87], is moving into the early stages of commercial deployment for urban logistics and captive fleets, where concerns over range and charging times are lower than for long-haul applications.

### 2.3.4. Future haulage propulsion technologies

Potential alternative fuels and propulsion technologies must display a particular set of properties, which include:

- High energy density (MJ/L) and specific energy (MJ/kg) to minimise fuel volume and mass and allow for long-distance travel
- Produce low levels of local emissions (SOx, NOx and PM), to ensure compliance with Euro VI emissions regulations
- Low energy costs (£/MWh), to ensure cost competitiveness with diesel fossils
- Low lifecycle GHG emissions (gCO2e/MJ), to reduce the climate impact of road freight
- Sufficient refuelling infrastructure across a region, to ensure vehicles are able to refuel regularly

The haulage sector has more flexibility than maritime or aviation as the placement of refuelling infrastructure along key routes allows fuels with lower specific energies and energy densities to be used. Furthermore, as the turnover rate for haulage fleets is typically much faster [11] than for shipping or aviation, the potential for retrofitting is less of a concern. However, due to the much higher levels of infrastructural requirements in comparison to shipping and aviation, infrastructural compatibility is an important consideration.

The use of biomethane/liquefied gas or biodiesel/renewable diesel as fuels for the haulage sector are promising options, especially as transition fuels that can utilise existing infrastructure while other technologies develop. Local conditions may dictate the suitability of each, but the vehicles and refuelling technologies can be deemed mature and lower cost than current alternatives.

Electrification is desirable as the efficiency of electric motors is much greater than combustion engines, and renewable electricity is an area in which great progress has been made. Plug-in hybrid and battery electric LGVs and MGVs operating in urban areas are moving into the early stages of commercial deployment aided by their lower gross vehicle weight and daily mileage [7,11]. However, HGVs that serve long-haul operations constitute the majority of the haulage sectors’ oil consumption, where battery size and mass presents a much larger hurdle to full electrification [11]. Battery electric vehicles (BEV) are now used in short-distance trucking (<400 km) [88], however, it is estimated for a BEV truck to have the same range as an equivalent diesel truck, the weight and space required for the batteries required would reduce the cargo capacity of the truck substantially [5]. Moreover, battery recharging times (~10 h) are far beyond the current acceptable refuelling times for long-haul trucks [88]. Analysis by Hoekstra indicates that the potential for battery electric vehicles is often underestimated [89]. Battery production learning curves and future improvements have the potential to have a large impact on the haulage sector. Future improvements in terms of battery specific energy and cost could increase the role of BEVs within the haulage sector. This is confirmed by Liimatainen et al., who show that using current battery technology 20% and 5% of haulage tonne-kilometres could be electrified in Switzerland and Finland respectively. This value rises to 71% and 35% for both Switzerland and Finland in a future scenario where the specific energy of batteries is tripled [90]. This analysis also highlights that the ability to electrify haulage is highly region specific, with the difference between Switzerland and Finland being accounted for by greater daily mileages and an increased use of heavy tractor-trailer units in Finland [90].

To solve this, Electric Road Systems (ERS) enable vehicles to receive a supply of electricity from power transfer installations along the road they are driving, decreasing the size of battery needed and increasing range [7,11]. The two main infrastructure options for ERS are conductive power transfer, where electricity is supplied to the vehicle via overhead catenary lines, or inductive power transfer, where coils that generate an electromagnetic field are installed in the road [7,11]. Both these options are under consideration, with pilot applications of catenary systems underway in Germany, Sweden and the USA [11]. ERS systems may be a promising option for vehicles that travel well defined routes along established freight corridors.

When compressed to 700 bar hydrogen in fuel cell HGVs addresses many of the technical issues surrounding the use of current state-of-the-art batteries (energy density and specific energy), allowing for greater ranges and cargo carrying capacity when compared with battery electric HGVs, and unlike ERS hydrogen allows operation outside of defined routes [11,91]. With hydrogen fuel cell vehicles becoming a commercial option for HGVs and buses, captive fleets are especially suited to the early adoption of hydrogen as an advanced fuel [92]. The Nikola Motor Company has announced the production of a fuel cell/battery hybrid truck with a claimed range of up to 750 miles, which is comparable to diesel alternatives [93]. In 2020, Hyundai delivered the first ten units of the hydrogen powered H2 Xcient HGVs for use in the Swiss market, with further plans to have 1600 on Swiss roads by 2025 [9]. Furthermore, Daimler has announced plans to develop the GenH2 Truck [9], a 40 t hydrogen powered HGV with a claimed range of up to 1000 km (Table 1) [24]. The lack of hydrogen refuelling infrastructure remains a significant barrier to large-scale uptake. An analysis of the Swiss heavy-duty transport sector indicates that conversion of the HGV fleet is tech-

| Table 4 |
| --- |
| Road freight vehicle classification [11,80,81]. |
| | Gross vehicle weight (t) | % of global fleet by number | Daily distance travelled (km) | Purpose |
| Light goods vehicles (LGV) | < 3.5 | 70 | 44 – 150 Average: 96 | Vans and small trucks used for small scale “last-mile” deliveries, such as postal or commercial delivery services |
| Medium goods vehicles (MGV) | 3.5 - 15 | 17 | 122 – 413 Average: 265 | Small two-axle lorries and rigid trucks used for regional delivery operations |
| Heavy goods vehicles (HGV) | > 15 | 13 | 263 – 792 Average: 507 | Large four and five axle tractor-trailers used for long-haul deliveries |
nically feasible, but significant decreases in GHG emissions are only seen when low carbon electricity is used to produce hydrogen via electrolysis [91].

3. Alternative fuels

3.1. Biomass-based fuels

To date, the conversion of biomass represents the only pathway that has been able to produce commercial quantities of non-fossil transporta-
tion fuels. Liquid biofuels currently provide 4.2% of the energy consumed by the transport sector worldwide, mainly in the form of ethanol produced from grains and sugar cane, and FAME biodiesel produced from oils [5]. These so-called first-generation biofuels are produced from edible feedstocks, and their production has been associated with issues such as increased food prices and land-use change [94]. The research and development of advanced second (non-edible) and third (free from competition for land with food) generation biofuels seeks to address these issues by implementing circular economy principles and utilising feedstocks such as forestry and agricultural residues, organic municipal wastes, algae and non-food energy crops (such as perennial grasses) [14].

3.1.1. Biomethane and Fischer-Tropsch fuels

Anaerobic digestion (AD) is a series of biological processes in which micro-organisms breakdown biodegradable organic matter in the absence of oxygen. The process results in the production of biogas, typically 55–70% CH4 and 30–45% CO2, and digestate. The digestate can be used as a nutrient source, reducing the demand for chemical fertilisers [95–97]. Traditionally used for electricity generation or combined heat and power (CHP), there has been increasing interest in upgrading biogas to biomethane (~97% CH4 content) by separating the carbon dioxide and injecting it into the natural gas network for use as an advanced transport fuel [95]. More recently, novel biogas upgrading technologies such as biological hydrogen methanation, where hydrogen reacts with the carbon dioxide to increase methane yields, have been under development [98]. Biomethane systems have the advantage of being able to use feedstocks that do not necessarily compete for land with food production such as grasses, agricultural wastes and municipal wastes [96]. Research into the potential for using non-land based feed-
stocks for AD, such as macro and micro-algae is also underway [96]. Some AD feedstocks (such as agricultural slurries) demonstrate low specific methane yields, meaning low volumes of methane are produced per kilogram of feedstock digested [99]. Current research involving direct interspecies electron transfer aims to improve the efficiencies and yields from AD through the addition of conductive materials (such as graphene or biochar) to the digester [100].

Gasification is a thermochemical process used to convert biomass into an intermediate gaseous product known as syngas (a mixture of primarily hydrogen and carbon monoxide), which can then be used to produce advanced biofuels [14,101,102] or separated such that the hy-
drogen can be used alone. A wide range of potential feedstocks can be used for the gasification process, such as lignocellulose (woody) biomass (such as short rotation coppice (SRC) willow), forestry residues, municipal and other wastes [103]. The raw syngas produced must be cleaned to remove any impurities before it can be used for the synthesis of liquid or gaseous hydrocarbons [14,102]. The resource of renewable gas can be greatly enhanced via gasification of lignocellulosic biomass followed by methanation, as demonstrated by Gallagher et al. [104]. While gasification is a mature technology that can, in theory, accept a wide range of feedstock, in practical terms only the gasification of homogenous feedstocks, such as coal and wood has been realised at commercial scales [14]. The technology readiness level (TRL) of heterogeneous biomass gasification (such as the organic fraction of municipal solid waste) is much lower. There are several key barriers that must be addressed in order for the gasification of renewable feedstocks to be viable at commercial scales, such as the removal of tar produced during the gasification process [14].

The Fischer-Tropsch (FT) process is a well-established process for converting syngas into liquid hydrocarbon fuels [101]. Fischer-Tropsch synthesis produces a range of liquid hydrocarbons that can be upgraded to “drop-in” replacements for petrol (gasoline), diesel and jet fuel [14]. Alternatively, the syngas could be catalytically converted into methanol which can be used directly in road transportation through blending with petrol, used in shipping in multi-fuel engines, or used to synthe-
sise dimethyl ether (DME), which can be used as an alternative fuel for diesel engines [14].

There are a number of additional positive externalities for both AD and gasification systems. Both AD and gasification systems are capable of utilising wastes, residues and non-food crops, enhancing their envi-
ronmental sustainability. Furthermore, biogas systems are effective waste management processes that can produce a bio-fertiliser (diges-
tate), reducing reliance on synthetic fertilisers and promoting a circular economy. Additionally, a large proportion of biogas feedstocks are rural, meaning that a biomethane/gasification industry has the potential to stimulate rural job creation [100]. It should be noted that AD and gasification are complementary rather than competitive technologies that can take advantage of a wide range of available resources.

3.1.2. Renewable diesels

As well as production via Fischer-Tropsch (which suffers from low selectivity), synthetic diesel transport fuels can be produced from lipid-based feedstocks (vegetable oils or animal fats) which are easier to pro-
cess and to upgrade to “drop-in” standard than lignocellulosic biomass or wet substrates [101]. The terms hydroprocessed esters and fatty acids (HEFA) or hydrotreated vegetable oils (HVO) [101] are used to distin-
guish more advanced fuels from traditional biodiesels, such as FAME biodiesel which is not considered to be a true “drop-in” fuel as it is sub-
ject to low blend limits [105]. The main advantage of HVO fuels is that they are highly compatible with existing infrastructure, and can be used in any one of the shipping, aviation or haulage sectors, although the lower density of HVO and other considerations mean that 100% blends are not yet approved [101]. As a direct “like-for-like” replacement for the incumbent liquid fossil fuels, HVO offer a very low resistance path-
way towards emissions reductions across all modes of heavy-duty trans-
port. With high industry buy-in, there is potential for immediate impact from the use of HVO [106]. However, there are concerns over the ability to produce HVO in a cheap and sustainable manner in the large quanti-
ties that would likely be required to meet the demand of the heavy-duty transport sector [101].

3.2. Hydrogen based fuels

The production of hydrogen and hydrogen-based synthetic fuels offers another pathway to the use of low-carbon transport fuels. Hydrogen can be produced from fossil fuels with or without carbon capture and storage (CCS), via water electrolysis from ideally renewable electricity, or less commonly from biomass. It can be stored either cryogenically as a liquid (~253 °C at atmospheric pressures) or as a compressed gas (700 bar) and used in a fuel cell or fuel cell/battery hybrid powertrain [5]. Besides its direct use in fuel cell applications, hydrogen is a key input in the production of synthetic energy carriers such as methane, methanol, ammonia and Fischer-Tropsch fuels [55].

3.2.1. Power-to-hydrogen and power-to-X

Low-carbon hydrogen via water electrolysis has been proposed as a key technology for storing excess variable renewable electricity (VRE), along with producing an advanced transport fuel [65]. Operating ide-
ally, electrolysis has been demonstrated as an effective method to help alleviate periods of curtailment (when electricity supply exceeds de-
mand) in power systems with high penetrations of variable renewable
energy (VRE) [57]. This concept is seen as complementary to ambitions for a fully renewable electricity system, synergistically coupling the transport and electricity sectors.

It is also possible to use hydrogen to produce synthetic hydrocarbons via the electrofuel (also called power-to-gas/liquid/fuel) concept [5,55]. Here, hydrogen is combined with a source of CO₂ to produce hydrocarbons such as methane (via methanation), methanol (via methanol synthesis) or petrol/diesel/jet fuel (via Fischer-Tropsch or Methanol-to-Gasoline synthesis), allowing for use of existing distribution and refuelling infrastructure [55]. CO₂ captured from industrial processes (such as cement production), biogenic processes (such as wastewater treatment plants or alcohol production facilities) or from direct air capture (DAC) are all suitable if it has been sufficiently cleaned and scrubbed of any impurities [55,107]. In terms of sustainability, the ideal CO₂ source is biogenic, relatively pure and located close to the PiX facility, in order to improve the GHG balance of the system and reduce costs [107]. Additionally, ammonia (NH₃) can be synthesised from renewable hydrogen using the Haber-Bosch process [5,55] and can be used as either a hydrogen carrier for fuel cell applications or in advanced dual-fuel engines [55]. The Kopernikus P2X project, based in Germany, aims to store renewable energy in the form of physical substances (hydrogen, synthetic fuels, chemicals) to help reach climate neutrality by 2050 [26]. Carbon Recycling International (CRI), based in Iceland, is an example of a commercial electrofuel facility, producing methanol from geothermal energy and CO₂ from the same source [27]. The Audi e-gas plant uses wind power and CO₂ from a biogas plant to produce methanol [108].

3.2.2. Hydrogen from fossil fuels with carbon capture and storage (CCS)

Steam reforming of natural gas and coal gasification are mature technologies for producing hydrogen from fossil fuels [109]. They currently account for 96% of global hydrogen production resulting in significant quantities of GHG emissions, with electrolysis only accounting for 4% [110]. Reforming or gasification of fossil fuels is capable of producing relatively pure hydrogen (~99.8%), but some impurities will remain. Fuel cell applications for transport require hydrogen with 99.999% purity to protect the catalysts, meaning hydrogen produced from fossil fuels may not be compatible without additional cleaning [110]. On the other hand, electrolysis produces very high purity hydrogen (~99.999%), meaning it is ideally suited to fuel cell applications for transport [110]. Therefore, hydrogen produced from fossil fuels in conjunction with CCS may be more suited to decarbonising other areas of the economy, such as industrial heating. Also it should be noted that the carbon capture process is not 100% effective, only capturing between 71% and 92% of the CO₂ emissions produced during the process, meaning that hydrogen produced from fossil fuels with CCS will still have a residual GHG footprint [111]. Electrolytic hydrogen may be more suited to transport too thanks to its smaller, more distributed decentralised production.

4. Fuel assessment criteria

4.1. Energy density

High energy densities (MJ/L) and specific energies (MJ/kg) are desirable qualities in fuels, as they imply the fuel requires less storage space and has a lower mass, which is especially beneficial when storing the fuel onboard a vehicle [29]. Both play a large role in determining the practical applications of a fuel.

The values seen in Fig. 5 do not account for overall system efficiency, which dictates how much fuel needs to be stored on board and will be discussed in Sections 4.1.1–4.1.3. As can be seen in Fig. 5, there is a wide variation in both specific energy and energy density for different energy carriers, with some energy carriers such as hydrogen showing significantly higher specific energy than conventional fuels but also having very low energy densities, while others such as FT diesel displays similar properties to conventional fuels. Liquid energy carriers (methanol, HVO, FT fuels, MtG) can easily be stored in existing fuel infrastructure, while energy carriers that are gaseous under standard temperature and pressure (such as hydrogen, biomethane, DME, ammonia) must be stored in cylinders as a compressed gas or liquid. Values for compressed and cryogenic hydrogen were taken from literature, while values for compressed or liquefied biomethane, DME and ammonia were calculated based on cylinder specifications. The inclusion of the fuel storage system can significantly reduce the energy density and specific energy of the energy carrier (Table 5).

Including the fuel storage system negatively affects the energy density/specific energy although each still outperforms current state-of-the-art lithium-ion batteries, which have a specific energy of 0.94 MJ/kg and an energy density of 2.63 MJ/L [117]. Additionally, it should be noted that improvements in energy storage are expected to be seen with scale, with larger tanks displaying more favourable specific energy and energy density. The energy density and specific energy presented in this section will then be used in a series of case studies to assess the viability of alternative fuels within the shipping, aviation and road haulage sectors.

4.1.1. Maritime shipping

The Pride of Hull is a large ferry (Table 6), able to accommodate 1360 passengers and 1380 vehicles [122]. The vessel operates on the Hull-Rotterdam route, entirely within the North Sea ECA, making it an ideal candidate to transition to low-sulphur, low-carbon propulsion.

Given the fuel capacity of the vessel (1000 m³), the energy stored onboard can be calculated based on the energy density of the fuel (Box 1). Then based on this value, the mass and volume required of alternative energy carriers required to give the vessel an equivalent range was calculated (Box 1); the output is presented in Table 7.

**Box 1.** – Mass of alternative energy carriers for maritime applications calculations

| Energy Stored Onboard Vessel – Baseline (Diesel) | Fuel Capacity = 1000 m³ = 1000,000 L | Diesel Energy Density = 35.98 MJ/L |
| Energy Content Onboard = 35,984,912 MJ = 35.98 TJ |
| Diesel Specific Energy = 42.93 MJ/kg |
| Mass of Fuel Onboard = 838,223 kg = 838 t |
| Energy Used for Propulsion – Baseline (Diesel) | Combustion Engine Efficiency = 45% [48] |
| Energy Used for Propulsion = 35,984,912 × 0.45 = 16,193,210 MJ |
| Energy Stored Onboard Vessel – Lithium Ion Battery | Li-ion Battery Specific Energy = 0.936 MJ/kg |
| Li-ion Battery Energy Density = 2.63 MJ/L |
| Mass of Battery Required (t_remaining = 100%) = 17,300,438 kg = 17,300 t |
| Volume of Battery Required (t_remaining = 100%) = 6157,114 L = 6757 m³ |
| Energy Stored Onboard Vessel – Compressed H₂ (700 bar) | Fuel Cell Efficiency = 55% [57] |
| Energy Required for Propulsion = 16,193,210/0.55 = 29,442,201 MJ |
| Compressed H₂ (700 bar) Specific Energy = 5.4 MJ/kg |
| Compressed H₂ (700 bar) Energy Density = 3.6 MJ/L |
| Mass of Compressed H₂ System Required = 5455,442 kg = 5445 t |
| Volume of Compressed H₂ System Required = 8178,389 L = 8178 m³ |

Similar calculations carried out for Cryogenic H₂, Compressed Biomethane (250 bar), Liquefied Biomethane, Ammonia, Methanol, HVO and FT Diesel, assuming a constant efficiency for all ICE pathways.

Using alternative energy carriers to give the vessel an equivalent range to the diesel baseline presents significant problems in terms of
1 Mass of fuel only, storage system (cylinders etc.) not included

Fig. 5. Specific energy versus energy density for different energy carriers. Sources [58,112–117].

|Fuel| Specific energy (MJ/kg) | Energy density (MJ/L)| Fuel storage system (filled)| Specific energy (MJ/kg) | Energy density (MJ/L)|
|---|---|---|---|---|---|
|Compressed H₂ (700 bar)| 120 [113]| 5.6 [113]| 5.4 [118]| 3.6 [118]|
|Cryogenic H₂| 120 [113]| 8.5 [119]| 8.99 [118]| 6.4 [118]|
|Compressed biomethane (250 bar)| 44.8 [112]| 7.8 [112]| 16.5 [120]| 5.9 [120]|
|Liquified biomethane| 44.8 [112]| 20.3 [112]| 17.8 [121]| 12.6 [121]|
|DME| 28.4 [115]| 19.03 [115]| 14.0 [121]| 11.9 [121]|
|Ammonia| 18.8 [58]| 11.3 [58]| 8.8 [121]| 7.2 [121]|

Table 6
Pride of Hull specifications.

|Name| Pride of Hull|
|---|---|
|Vessel type| Roll-on/Roll-off passenger ferry (Ro-Pax)|
|Overall length| 215 m|
|Beam| 32 m|
|Main engine power| 37.8 MW|
|Fuel capacity| 1000 m³|
|Maximum speed| 22 knots|
|Dead weight tonnage| 8850 t|
|Route| Hull (UK) to Rotterdam (The Netherlands)|
|Voyage average speed| 17.8 knots|
|Voyage time| 11.9 h|

mass and volume (Table 7), as the mass of the battery alone would be approximately twice the DWT of the vessel. Similarly, the use of compressed hydrogen would take up 62% of the ships DWT. Fuels such as compressed biomethane and methanol, while being more energy-dense than batteries and hydrogen still result in an increase in fuel mass and storage volume, with only drop-in fuels such as HVO and FT diesel offering similar energy densities.

Instead of ensuring the vessel powered by alternative fuel has an equivalent range to the baseline configuration, the problem was reanalysed utilising the existing mass and volume of fuel to calculate the new potential range as may be the case in a retrofit. For the Pride of Hull,
which has a regular scheduled route, the energy required for a single one-way trip was calculated (Box 2).

**Box 2. - Energy required for one-way Hull to Rotterdam voyage** [122]

| Energy Based on Available Fuel Mass (TJ) | Energy Based on Available Fuel Volume (TJ) | Limiting Factor that gives highest value | Energy Based Limiting Factor (TJ) | Energy Required for One-Way Trip (TJ) | Number of Possible One-Way Trips |
|------------------------------------------|-------------------------------------------|----------------------------------------|----------------------------------|--------------------------------------|----------------------------------|
| Diesel (Baseline, \(\eta_{\text{c}} = 45\%\)) | 35.98 | 35.98 | N/A | 35.98 | 1.91 | 18.88 |
| Li-ion Battery \(\eta_{\text{c}} = 45\%\) | 0.785 | 2.63 | Mass | 0.785 | 0.858 | 0.91 |
| Compressed H\(_2\) (700 bar, \(\eta_{\text{c}} = 55\%\)) | 4.52 | 3.60 | Volume | 3.60 | 1.56 | 2.31 |
| Cryogenic H\(_2\) \(\eta_{\text{c}} = 55\%\) | 7.54 | 6.40 | Volume | 6.40 | 1.56 | 4.10 |
| Compressed Biomethane \(\eta_{\text{c}} = 55\%\) | 13.8 | 5.94 | Volume | 5.94 | 1.91 | 3.12 |
| Liquified Biomethane \(\eta_{\text{c}} = 45\%\) | 14.9 | 12.6 | Volume | 12.6 | 1.91 | 6.63 |
| Ammonia \(\eta_{\text{c}} = 45\%\) | 7.38 | 7.17 | Volume | 7.17 | 1.91 | 3.76 |
| Methanol \(\eta_{\text{c}} = 45\%\) | 16.5 | 15.6 | Volume | 15.60 | 1.91 | 8.18 |
| HVO \(\eta_{\text{c}} = 45\%\) | 35.4 | 33.0 | Volume | 33.00 | 1.91 | 17.31 |
| FT Diesel \(\eta_{\text{c}} = 45\%\) | 36.7 | 34.5 | Volume | 34.50 | 1.91 | 18.10 |

**4.1.2. Aviation**

Unlike ships, aircraft carry only the minimum safe mass of fuel required to complete a flight as stipulated by EASA regulations (Table 9) [123].

Similar calculations were performed for the aircraft as were performed for the ship (Box 3 and Table 10).

**Box 3. - Mass of alternative energy fuels for aviation applications calculations**

The average and maximum speeds are used to find the engine Load Factor (LF):

\[
\text{Load Factor (LF)} = \left( \frac{\text{Average Speed (knots)}}{\text{Maximum Speed (knots)}} \right)^3 = \left( \frac{17.8}{22} \right)^3 = 0.53
\]

From here, the LF is multiplied by the installed engine power to give the average shaft power output over the course of the voyage:

\[
\text{Average Shaft Power (MW)} = \text{LF} \times \text{Engine Power (MW)} = 0.53 \times 37.8 = 20.02 \text{ MW}
\]

In order to calculate the total energy for the voyage the average shaft power is multiplied by the voyage time, which can then be converted into MJ:

\[
\text{Voyage Energy (MW h)} = \text{Average Shaft Power (MW)} \times \text{Voyage Time (hours)} = 20.02 \times 11.9 = 238.25 \text{ MW h} = 857.696 \text{ MJ}
\]

\[
\text{Energy Onboard Aircraft – Baseline (Jet Fuel)}
\]

- Short/Medium-Haul Total Fuel Mass = 7200 kg [123]
- Jet Fuel Specific Energy = 43.92 MJ/kg
- Jet Fuel Energy Density = 35.11 MJ/L
- Energy Content Onboard = 316,224 MJ
- Fuel Volume = 9007 L
- Energy Used for Propulsion – Baseline (Jet Fuel)
- Gas Turbine Efficiency = 40% [126]
- Energy Used for Propulsion = 316,224 × 0.4 = 126,490 MJ

**Energy Onboard Aircraft – Lithium-Ion Battery**

Energy Used for Propulsion \((\eta_{\text{drivetrain}} = 100\%) = 126,490 \text{ MJ}

Li-ion Battery Specific Energy = 0.936 MJ/kg
- Li-ion Battery Energy Density = 2.63 MJ/L
- Mass of Battery Required = 135,138 kg = 135.2 t
- Volume of Battery Required = 48,095 L

**Energy Onboard Aircraft – Compressed H\(_2\) (700 bar)**

Energy Used for Propulsion \((\eta_{\text{fuel cell}} = 55\%) = 126,490/0.55 = 229,981 \text{ MJ}

Compressed H\(_2\) Specific Energy = 5.4 MJ/kg
- Compressed H\(_2\) Energy Density = 3.6 MJ/L
- Mass of Compressed H\(_2\) and Storage System = 42,614 kg = 42.6 t
- Volume of Compressed H\(_2\) and Storage System = 63,884 L

Similar calculations carried out for Cryogenic H\(_2\), Compressed Biomethane, Liquidified Biomethane, HVO, FT Jet Fuel and MtG Jet Fuel for both short/medium-haul flights and long-haul flights.

The use of batteries to power aircraft for both short/medium and long-haul flights is impracticable given the current state-of-the-art of battery technology (Table 10). For short/medium-haul flights the mass
of the battery required to store the energy needed would be 1.7 times the maximum allowed take-off weight of the aircraft, whereas for long-haul flights the mass of the battery required would be 3.8 times the maximum allowable take-off weight. Similarly, the use of compressed or cryogenic hydrogen and compressed or liquified biomethane presents issues as the mass and volume required to store the fuel would negatively affect the payload carrying capacity of the aircraft. Without a significant transformation of the aviation industry, only through the use of drop-in fuels such as HVO, FT jet fuel or MtG jet fuel can similar aircraft ranges and payloads be seen when compared to the baseline configuration.

### 4.1.3. Haulage

For the purposes of assessing the feasibility of low-carbon technologies for HGVs, a 40-t articulated truck, consisting of tractor and trailer unit was selected for analysis, details of which can be seen in Table 11 [127]. Typical operation for this class of HGV is long motorway journeys at constant speed, with little urban driving.

Using these values, the mass and volume of alternative energy carriers required to give the HGV studied an equivalent range to the diesel baseline were calculated (Box 4) with results presented in Table 12.

#### Table 9
EASA fuel regulations for short/medium and long-haul flights [123].

| Aircraft Route | Short/Medium-Haul Flight | Long-Haul Flight |
|----------------|--------------------------|------------------|
| Example Route  | Dublin to Frankfurt (~1000 km) | London to Buenos Aires (~11,000 km) |
| Aircraft Variant | Boeing 737-800 | Airbus A380 |
| Taxi Fuel (kg) | 250 | 500 |
| Trip Fuel (kg) | 400 | 98,854 |
| Contingency Fuel (kg) | 200 | 4993 |
| Alternate Fuel (kg) | 1500 | 3338 |
| Discretionary Fuel (kg) | 250 | 800 |
| Final Reserve Fuel (kg) | 1000 | 2961 |
| Total Fuel (kg) | 7200 | 112,446 |
| Aircraft Maximum Take-off Weight (kg) | 79,015 [124] | 560,000 [125] |

#### Table 10
Mass and volumes of fuels required for short/medium and long-haul flights.

| Fuel/Mass-Haul Flight | Short/medium-Haul Flight | Long-Haul Flight |
|-----------------------|--------------------------|------------------|
| Jet Fuel (Baseline)   | 7200 | 112,446 | 20.1% |
| Li-ion Battery        | 135,138 | 2110,525 | 377% |
| Compressed H₂ (700 bar) | 42,614 | 665,523 | 119% |
| Cryogenic H₂ Compressed Biomethane (250 bar) | 25,568 | 399,655 | 71.3% |
| Liquified Biomethane HVO | 17,791 | 277,849 | 49.6% |
| FT Jet Fuel | 7220 | 117,254 | 20.1% |
| MtG Jet Fuel | 6815 | 106,436 | 19.0% |

#### Table 11
40-t articulated HGV specifications.

| Fuel | Engine Power (kW) | Fuel Consumption (L/100 km) | Fuel Tank Capacity (L) | Range (km) | Gross Combined Weight (kg) | Total Kerb Weight (kg) | Payload (kg) |
|------|-------------------|-----------------------------|------------------------|------------|---------------------------|-----------------------|-------------|
| Diesel | 326 | 35 [128] | 450 | 1216 | 40,000 | 14,550 [81] | 25,450 [81] |

#### Box 4.
- Mass of alternative energy fuels for HGV applications calculations

**Energy Onboard HGV – Baseline (Diesel)**
- Fuel Tank Capacity = 450 L [127]
- Diesel Specific Energy = 42.93 MJ/kg
- Diesel Energy Density = 35.98 MJ/L
- Energy Content Onboard = 16,193 MJ
- Fuel Mass = 377 kg

**Energy Used for Propulsion – Baseline**
- Combustion Engine Efficiency = 39%
- Energy Used for Propulsion = 16,193 MJ x 0.39 = 6332 MJ

**Energy Onboard HGV – Li-Ion Battery**
- Energy Used for Propulsion ($\eta_{\text{Drivertrain}} = 100\%$) = 6332 MJ
- Li-ion Battery Specific Energy = 0.936 MJ/kg
- Li-ion Battery Energy Density = 2.63 MJ/L
- Mass of Battery Required = 6764 kg
- Volume of Battery Required = 2407 L

**Energy Onboard HGV – Compressed H₂ (700 bar)**
- Energy Used for Propulsion ($\eta_{\text{fuel cell}} = 55\%$) = 6332/0.55 = 11,512 MJ
- Compressed H₂ Specific Energy = 5.4 MJ/kg
- Compressed H₂ Energy Density = 3.6 MJ/L
- Mass of Compressed H₂ and Storage System = 2133 kg
- Volume of Compressed H₂ and Storage System = 3198 L
- Similar calculations carried out for Cryogenic H₂, Compressed Biomethane, Liquified Biomethane, DME, HVO and FT Diesel

Evidence shows that trucks rarely utilise their full range, with their maximum daily mileage being approximately 800 km [81]. It is therefore possible to calculate the mass and volume of alternative energy carriers required to provide an 800 km range (Box 5) with the results presented in Table 12. Calculations for a vehicle with a range of 500 km
have also been carried out in a similar manner, to represent a vehicle that would refuel once per day.

**Box 5. - Energy required for HGV 800 km range**

| Energy Efficiency – Baseline (Diesel) |
|--------------------------------------|
| Fuel Consumption = 37 L/100 km = 13.31 MJ/km |
| ICE Efficiency = 39% |
| Energy Used for Propulsion = 13.31 × 0.39 = 5.21 MJ/km |
| Li-Ion Battery (800 km range) |
| Energy Used for Propulsion (n_drivertrain = 100%) = 5.21 MJ/km |
| Energy Storage Required = 5.21 MJ/km × 800 km = 4165 MJ |
| Li-Ion Battery Specific Energy = 0.936 MJ/kg |
| Li-Ion Battery Energy Density = 2.63 MJ/L |
| Mass of Battery Required = 4550 kg |
| Volume of Battery Required = 1584 L |
| Similar calculations carried out for Compressed H2, Cryogenic H2, Compressed Biomethane, Liquified Biomethane, DME, HVO and FT Diesel |

While the use of battery electric trucks may be technically feasible, in the Equivalent Range and 800 km Range Scenarios the weight penalty and associated decrease in payload capacity with the use of Li-ion batteries in trucks is likely beyond acceptable limits of haulage firms without also experiencing substantial drops in operating costs. In the 500 km range scenario, the payload decrease is only 9% which may be deemed as acceptable by haulage firms. Therefore, there is good potential for shorter range operations to be electrified. Both compressed and cryogenic hydrogen offer superior performance to batteries and offer a technically viable alternative for zero-tailpipe emissions haulage. Energy carriers such as compressed/liquified biomethane and DME perform similarly, while drop-in fuels such as HVO and FT diesel offer comparable performance to the baseline diesel configuration.

### 4.2. Costs

#### 4.2.1. Fuel costs

Over the lifetime of a vehicle in each of these sectors, fuel comprises a significant portion of operating costs, 33% for aviation [76], 50% for maritime [34], and 38% [32] for haulage. Therefore, the levelised cost of energy (LCOE) for each fuel must be considered. A range of costs for fossil fuels, biofuels and electrofuels can be seen in Table 13.

From Table 13, it is obvious that the majority of alternative fuels struggle to be competitive with current fossil fuel prices. This is especially true for the maritime and aviation sectors. The prevalence of low-quality residual fuels in the shipping sector results in low fuel costs, whereas fuel used for aviation remains exempt from tax due to bilateral international aviation agreements known as Air Service Agreements [8,34]. For biofuels, the cost of raw material (biomass) [133] and the process conversion efficiency [134] have been shown to have the largest impact on fuel costs, while economies of scale are generally required to minimise the levelised cost of energy (LCOE) [136,137]. McDonagh et al. indicated that electricity cost and the number of operating hours are the parameters that have the largest effect on the LCOE of electrofuels [56]. It has been suggested that electrofuels may operate only at times of excess renewable electricity production, but McDonagh et al. demonstrated that the potential for utilising only otherwise curtailed electricity alone is low [139]. Therefore, engaging in the electricity market as a consumer is necessary to increase the number of run hours to amortise the investment in an electrofuel production facility [139]. Due to the additional processing steps required to produce fuels via the P2X concept, the production of synthetic liquid and gaseous fuels will always be more expensive than the hydrogen used as an input, therefore from an economic perspective, it makes sense to utilise hydrogen directly wherever possible. However, as highlighted in Section 4.1 this may not always be possible due to volume and payload constraints.

In order to make a fair comparison between fuels, fuel costs for the haulage sector were calculated on a €/100 km basis (Table 13), considering differing powertrain efficiencies for combustion engine, battery electric and fuel cell vehicles. Results for both battery electric and fuel cell HGVs indicate that it is possible for alternative fuels to be more expensive than diesel and still reduce operating costs due to increased powertrain efficiency. Conversely, alternative fuels that utilise combustion engine technology must cost less than or equal to diesel in order for operational cost savings. Similar trends are expected to be seen in the shipping and aviation sectors. It should be noted that although fuel costs make up a significant portion of total costs, other costs such as capital expenditure and operating and maintenance costs also affect the overall system costs. A total cost of ownership analysis would be required to assess how the overall system costs of alternatively fuelled vehicles compares with fossil fuel equivalents.

It should also be noted that there is still a large amount of uncertainty surrounding future fuel costs, especially for emerging technologies such as hydrogen, batteries and electrofuels and these costs are strongly af-
fects by learning curves. Learning curves are typically defined as the costs of a technology decreasing over time due to increased deployment and innovation and are commonly represented as the cost reduction seen with a doubling of deployment [140]. The rate of doubling can vary greatly and is dependant on technological breakthroughs or policy drivers to encourage the uptake of new technologies.

### 4.2.2. Vehicle costs

The additional capital costs associated with the use of alternative fuels and powertrains are mainly comprised of the cost of storage (such as high pressure cylinders or batteries) and the cost of the energy converter (such as fuel cell and motors) (Table 14). The use of drop-in fuels, such as HVO or FT-diesel has significant advantages here as they are compatible with existing vehicle technologies. The IEA estimate that a HGV operating using CNG costs approximately $22,000 more than a conventional HGV, while a LNG powered HGV costs $40,000 more than a diesel HGV [11]. In shipping, greater costs are expected for vessels that utilise alternative energy carriers such as LNG or hydrogen [29]. The use of alternative fuels and powertrains (such as fuel cell electric) in the aviation sector is still in the early stage of research and development, and therefore the cost of alternative aircraft is uncertain although likely to be substantially higher.

Current estimates for the cost of fuel cells range from €170/kW to €250/kW [32,143]. Technical assessments indicate that there is significant potential to reduce fuel cell costs to between €50/kW and €70/kW through high-volume manufacturing with next-generation technologies though the reductions are dependant on the extent to which fuel cell vehicles are adopted [31,32,143]. The IEA estimate that given current hydrogen storage and fuel cell technology, a fuel cell HGV costs approximately $370,000 more than a standard diesel HGV, with this gap is predicted to fall to between $30,000 and $110,000 if improvements in fuel cell technology are seen [11].

The cost of battery storage is currently significantly higher than the cost to store gaseous or liquid fuels, which will likely be prohibitively

### Table 13

Conventional and alternative fuel costs.

| Fuel Costs per MWh (/€/MWh) | Fuel Costs per 100 km (/€/100 km) | Notes |
|-------------------------------|-----------------------------------|-------|
| **Fossil Fuels**              |                                   |       |
| Diesel                        | 109 [129]                         | 38.26 | Average 2020 diesel price excluding VAT (fuel duty comprises €59.6/MWh) |
| Jet Fuel                      | 45 [76]                           | N/A   | Conventional jet fuel |
| HFO                           | 36 [130]                          | N/A   | Average 2020 Low-Sulphur HFO price |
| Natural Gas                   | 38.2 [131]                        | 16.44 | Average EU-28 natural gas price |
| **Biofuels**                  |                                   |       |
| Biomethane                    | 91 – 144 [132–134]                | 38.51 – 61.97 | Anaerobic digestion of grass silage and cattle slurry |
| Biomethane                    | 60 – 90 [135,136]                 | 27.37 – 37.14 | Gasification of lignocellulosic biomass |
| Methanol                      | 75 – 144 [136,137]                | N/A   | Gasification of lignocellulosic biomass |
| DME                           | 90 – 110 [108]                    | 31.49 – 38.48 | Gasification of lignocellulosic biomass |
| Hydrotreated vegetable oil    | 140 – 195 [138]                   | 49.71 – 69.68 | HVO from palm oil |
| FT Diesel                     | 100 – 630 [14,138]                | 34.36 – 220 | Gasification of lignocellulosic biomass |
| **Electrofuels**              |                                   |       |
| Hydrogen                      | 110 – 200 [57]                    | 27.36 – 49.74 | Corresponds to 3300 and 6300 electrolysis run hours respectively |
| Methane                       | 120 – 650 [108]                   | 51.64 – 279.71 | 80% electrolysis capacity factor |
| Methanol                      | 120 – 680 [108]                   | N/A   | 80% electrolysis capacity factor |
| DME                           | 120 – 690 [108]                   | 41.98 – 241.40 | 80% electrolysis capacity factor |
| FT Diesel                     | 130 – 770 [108]                   | 45.48 – 269.39 | 80% electrolysis capacity factor |
| Methanol-to-Gasoline          | 160 – 1050 [108]                  | 55.98 – 376.35 | 80% electrolysis capacity factor |
| Ammonia                       | 60 – 130 [55]                     | N/A   | 3000 electrolysis run hours |
| **Battery Electric**          |                                   |       |
| EU28                          | 122 [131]                         | 17.63 | Average electricity price for industrial consumers within the EU |
| **Ireland**                   | 135 [131]                         | 19.57 | Average electricity price for industrial consumers within Ireland |

1 Road haulage sector only.

### Table 14

Onboard fuel storage costs for haulage.

| Storage System          | Cost (/€/MJ stored) | Fuel Storage Costs for HGV with 800 km Range |
|-------------------------|---------------------|--------------------------------------------|
| Diesel – Baseline Comparator | 0.07 [42]           | € 745.61                                   |
| Compressed Biomethane (250 bar) | 1.25 [11]           | € 13,314.42                                |
| Liquefied Biomethane     | 2.14 [11]           | € 22,794.28                                |
| Compressed Hydrogen (700 bar) | 2.48 [118]          | € 18,779.24                                |
| Cryogenic Hydrogen       | 2.87 [141]          | € 21,732.42                                |
| Li-ion Batteries         | 41.67 – 555.56 [117,142] | € 173,545.12 – 2313,768                  |
Table 15
WTW life cycle emissions.

|               | Well to Tank Emissions Factor (gCO2e/MJ) | Tank to Wheel Emissions Factor (gCO2e/MJ) | Well to Wheel Emissions Factor (gCO2e/MJ) | Emissions per 100 km (kgCO2e/100 km) | Notes |
|---------------|------------------------------------------|-------------------------------------------|------------------------------------------|-----------------------------|-------|
| **Fossil Fuels** |                                          |                                           |                                          |                              |       |
| Diesel        | 17.4 [112]                               | 72.1 [112]                               | 89.5                                     | 112.71                      |       |
| Jet Fuel      | 15.0 [112]                               | 72.4 [112]                               | 87.4                                     | N/A                         |       |
| HFO           | 15.0 [112]                               | 79.1 [112]                               | 94.1                                     | N/A                         |       |
| CNG           | 10.9 [112]                               | 56.7 [112]                               | 67.6                                     | 104.78                      |       |
| LNG           | 19.6 [112]                               | 56.9 [112]                               | 76.5                                     | 118.54                      |       |
| **Biofuels**  |                                          |                                           |                                          |                              |       |
| Biomethane    | –85.5 – 45 [95,144–148]                  | 0                                         | –85.5 – 45                               | –132.5 – 69.7               | Anaerobic digestion |
| Methanol      | 36 – 46 [151]                            | 0                                         | 36 – 46                                  | N/A                         | Gasification of lignocellulosic biomass |
| DME           | 25 – 74.3 [152,153]                      | 0                                         | 25 – 74.3                                | 31.5 – 93.6                 | Gasification of lignocellulosic biomass |
| HVO           | 30.1 – 698 [25]                          | 0                                         | 30.1 – 698                               | 37.9 – 879                  | Palm oil |
| FT Diesel     | 17 – 109 [154]                           | 0                                         | 17–109                                   | 21.4 – 137                  | Gasification of lignocellulosic biomass |
| **Electrofuels** |                                        |                                           |                                          |                              |       |
| Grid average electricity – Irish Mix [155] | 139                                             | 0                                         | 139                                      | 124                         | Grid average electricity, Irish generation mix in 2018. |
| Hydrogen      | 139                                      | 0                                         | 139                                      | 124                         |       |
| Methane       | 180                                      | 0                                         | 180                                      | 279                         |       |
| Methanol      | 176                                      | 0                                         | 176                                      | N/A                         |       |
| DME           | 174                                      | 0                                         | 174                                      | 219                         |       |
| FT Diesel     | 190                                      | 0                                         | 190                                      | 240                         |       |
| Methanol-to-Gasoline | 204                                      | 0                                         | 204                                      | 257                         |       |
| Ammonia       | 173                                      | 0                                         | 173                                      | N/A                         |       |
| **Wind electricity** [156] |                                        |                                           |                                          |                              |       |
| Hydrogen      | 2.59 – 20.74                             | 0                                         | 2.59 – 20.74                             | 2.32 – 18.57                | Electricity generated from wind energy. |
| Methane       | 3.37 – 26.94                             | 0                                         | 3.37 – 26.94                             | 5.22 – 41.73                |       |
| Methanol      | 3.28 – 26.25                             | 0                                         | 3.28 – 26.25                             | N/A                         |       |
| DME           | 3.24 – 25.93                             | 0                                         | 3.24 – 25.93                             | 4.08 – 32.65                |       |
| FT Diesel     | 3.55 – 28.41                             | 0                                         | 3.55 – 28.41                             | 4.47 – 35.78                |       |
| Methanol-to-Gasoline | 3.81 – 30.5                             | 0                                         | 3.81 – 30.5                              | 4.8 – 38.42                 |       |
| Ammonia       | 3.24 – 25.93                             | 0                                         | 3.24 – 25.93                             | N/A                         |       |
| **Solar PV electricity** [156] |                                        |                                           |                                          |                              |       |
| Hydrogen      | 6.67 – 66.67                             | 0                                         | 6.67 – 66.67                             | 5.97 – 59.69                | Electricity generated from solar energy. |
| Methane       | 8.66 – 86.58                             | 0                                         | 8.66 – 86.58                             | 13.41 – 134.13              |       |
| Methanol      | 8.44 – 84.39                             | 0                                         | 8.44 – 84.39                             | N/A                         |       |
| DME           | 8.33 – 83.33                             | 0                                         | 8.33 – 83.33                             | 10.5 – 104.96               |       |
| FT Diesel     | 9.13 – 91.32                             | 0                                         | 9.13 – 91.32                             | 11.5 – 115.02               |       |
| Methanol-to-Gasoline | 9.80 – 98.04                        | 0                                         | 9.80 – 98.04                             | 12.35 – 123.48              |       |
| Ammonia       | 8.33 – 83.33                             | 0                                         | 8.33 – 83.33                             | N/A                         |       |
| **Battery Electric** |                                      |                                           |                                          |                              |       |
| Grid average electricity – Irish Mix [155] | 104.7                                   | 0                                         | 104.7                                   | 51.3                         | Grid average electricity, Irish generation mix in 2018. |

Notes: 
1. Road haulage sector only.

high for many heavy-duty applications (Table 14). In applications where batteries are applicable though, the efficiency improvements and thus, reduced running costs may provide sufficient incentive.

4.3. Well-to-wheel GHG emissions

Well-to-wheel (WTW) lifecycle emissions are used for assessing alternative fuels for transport and are perhaps the most important criteria to consider [142]. WTW studies comprise of the well-to-tank (WTT) phase including the recovery/production of the feedstock/product, energy conversion, delivery and storage, and the tank-to-wheel (TTW) phase including onboard conversion of the energy carrier to provide propulsion [142]. WTW emissions factors for a range of fossil fuels, biofuels and electrofuels can be seen per MJ of fuel used in Table 15, with real-life emissions influenced by various parameters such as vehicle efficiency and driving conditions.

While fossil CNG and LNG have lower emissions factor (gCO2e/MJ) than diesel, the lower efficiency of natural gas vehicles meant that only a slight reduction in emissions on a gCO2e/100 km basis is seen for CNG, while LNG leads to an increase of 5% in GHG emissions per 100 km, which aligns with results presented by Langshaw et al. [85].

In the recast EU Renewable Energy Directive (RED) biofuel emissions consist only of the WTT phase as it is assumed their combustion is carbon neutral [10]. Emissions from biofuels produced from wastes or residues or biomass grown on marginal land are generally credited with lower emissions than from crops specifically grown for energy produc-
tion. The choice of feedstock for biofuel production then has a strong influence on the overall sustainability of the system along with the emissions associated with artificial fertiliser use [144,147,157]. Additionally, how emissions are allocated among products plays a large role in determining the lifecycle emissions of the system. Thamsiriroj et al. reported that AD of grass silage has a carbon intensity of 41 gCO₂e/MJ when all the emissions are allocated to the produced biomethane. Expanding the scope to include the benefits of grassland carbon sequestration, along with digestate replacing artificial fertilisers, the carbon intensity could be argued to fall to ~26 gCO₂e/MJ [145]. Furthermore, when animal slurries are used as a feedstock for biomethane production, the avoided emissions from traditional manure management techniques mean the carbon intensity could fall even further to a value of ~85.5 gCO₂e/MJ [148]. The inclusion of both direct (when an energy crop displaces prior land use) and indirect (displacing a food crop results in forest or grassland being used for food crop production to compensate for the resulting gap in production) land use change emission for biofuel systems is a controversial topic [158]. The inclusion of both direct and indirect land use change emissions can have a significant negative effect on the lifecycle emissions of biofuel systems, especially for systems that utilise crops specifically grown for energy production; this explains the large variation in WTW emissions for HVO produced from palm oil in Table 15. The overall sustainability of HVO fuels is an ongoing concern as sourcing vegetable oils at commercial scales likely means growing oilseed crops purposefully on land that could displace natural habitats or otherwise be used for food production [101]. If indirect land-use change (ILUC) effects are taken into account the overall lifecycle impacts of certain HVO fuels could be substantially higher than their equivalent fossil fuel [25]. Concerns over sustainability can be addressed by utilising waste cooking oils, however, the resource potential for sustainable HVO fuels may be limited [101].

The lifecycle GHG emissions of electrofuel production are almost dominated by the carbon intensity of the electricity used to produce hydrogen via electrolysis [15,57]. Electrolysis efficiency dictates that the carbon footprint of the hydrogen is always proportionally larger than the electricity used to produce it. Furthermore, inefficiencies in the synthesis of fuels such as methane or FT diesel mean than they will have higher carbon intensities than the hydrogen used in the fuel production. The exclusive use of renewable electricity in the electrolysis process leads to a low carbon intensity (Table 15). However, as work by McDonagh et al. indicates, in order to economically optimise the electrofuel system, only using renewable electricity currently leads to a prohibitively high LCOE [57]. Use of grid electricity in electrolysis can lead to very high carbon intensities though, especially if the electrical grid is still reliant on fossil fuels, such as coal. This means that electrofuels produced using grid electricity can have a greater carbon intensity on a per 100 km basis than diesel, unless the carbon intensity of the electrical grid is very low. To improve the environmental sustainability without sacrificing economic viability of electrofuel plants, McDonagh et al. utilised operational controls (bid price and wind forecast controls) in an attempt to lessen the likelihood of operating during times of high carbon intensity electricity [57]. Consuming low-cost electricity which is hypothesised to be analogous to low carbon renewable electricity, or only operating when the forecasted wind energy is predicted to be over a certain threshold (such as 150% of average wind generation) were seen to have significant positive synergistic effects. The controls reduced both the carbon footprint and electricity cost when compared with grid average electricity. Such controls are compatible with modern electricity markets and allow sustainable electrofuel production in advance of a 100% renewable system [57].

The source of CO₂ for synthetic fuel production is also an area of concern. If the CO₂ used in the production of electrofuels is atmospheric (from direct air carbon capture) or is biogenic in origin (such as the CO₂ released when biogas is upgraded to biomethane or from distilleries), the prevailing convention is to treat the combustion of the fuel as carbon neutral [15]. If the CO₂ is sourced from a waste stream that would otherwise be released into the atmosphere (such as fossil fuel power plant flue gas), methodological care must be taken to ensure that the emissions reductions are not double counted in both the transport and power sectors. Furthermore, use of CO₂ from industrial processes could give large-scale emitters the incentive to continue emitting carbon dioxide and lead to fossil fuel lock-in. Currently, capturing CO₂ from point sources such as power plants is much more cost effective than direct air capture technologies [15]. In the short to medium term industrial sources of fossil CO₂ may be acceptable to kickstart the electrofuel industry before DAC or biogenic sources are used, in order to ensure sustainability.

While GHG emissions per 100 km have only been analysed here for the haulage sector, similar trends can be expected to be seen across the shipping and aviation sectors.

4.4. Land area

As land area is a finite resource, the energy yield per hectare of land is an important factor to consider. Of the 13 Gha of global ice-free land area, only 12% is devoted to crop production, 37% is used for pasture-land, 22% used for forestry and 28% is marginal land or land otherwise unused for human activity [159]. From a sustainability perspective, it is preferable to utilise wastes, residues and feedstocks grown on marginal land before considering the growth of dedicated energy crops.

The choice of alternative fuel is highly dependant on regional conditions and the land area required will vary on the specifics of each fuel and on climatic and agricultural conditions. To illustrate the challenges faced, the potential for various crops in Ireland, a temperate region, was investigated. As an island nation, with a relatively low population density, Ireland is heavily reliant on shipping, aviation and haulage (Fig. 6) [155].

When considering alternative fuels, the land area required to produce the fuel is an important aspect to consider. Under Irish conditions, Smyth et al. investigated the energy balance of grass biomethane, finding that gross energy yields of 122 GJ/ha/yr were achievable [97]. Sim-
Fig. 7. Land take required to meet Ireland’s heavy-duty transport energy needs.

Similarly, Thamsiriroyj et al. found that the gross energy balance of biodiesel produced from rapeseed oil in Ireland has a gross energy balance of 47 GJ/ha/yr [145]. The energy balance of HVO produced from palm oil is significantly higher, at 162 GJ/ha/yr, but can only be produced in tropical climates, therefore would need to be imported into Ireland [25]. In the case of electrofuel production from VRE sources, most of the land take comes from the installation of photovoltaic panels or wind turbines, with values in the literature vary from 450 to 0 GJ/ha/yr for electrofuel production from VRE [15,25,160]. Taking a conservative estimate of 500 GJ/ha/yr for electrofuel production, the land take required to meet Ireland’s heavy-duty transport requirement can be seen in Fig. 7.

Currently, 3.9 million ha of Irish farmland is used to grow grass, meaning approximately a quarter of Irish grass land would be required to meet Ireland’s heavy-duty transport needs [97] or else production per hectare would need to increase by 25%. Approximately 400,000 ha of Irish agricultural land is devoted to crop production, meaning that if indigenous rapeseed biodiesel was to be used to fulfil the needs of heavy-duty transport, grassland or forest would need to be converted to arable land, leading to direct land use change emissions. The land associated with rapeseed is exasperated by the fact that rapeseed is typically grown in a rotation of one year in four; it is not suitable for cultivation on the same land for consecutive years. It is evident that the land required for electrofuel production is superior to biofuel systems. Furthermore, the increased electrical demand caused by electrofuel production could be met by the installation of offshore wind farms or renewables placed on marginal land, reducing the land take required further. It should be noted that the choice of alternative fuel is highly dependant on regional conditions, with Ireland’s grass resource not being representative of conditions worldwide.

4.5. Summary

In Fig. 8, a diagram summarising the performance of each alternative fuel pathway against the selected assessment criteria is presented. A “traffic light” colour scheme has been applied to indicate the relative performance of each fuel pathway. In general, the low energy density of battery technologies precludes their use in the shipping and aviation sectors, while the nature of the haulage sector means the barriers to electrification are lower.

Alternative fuels struggle to compete on costs with fossil fuels, however the greater efficiencies of fuel cell and battery electric powertrains allow for more expensive fuels to be used before an increase in operating costs is seen. “Drop-in” fuels are able to take advantage of existing vehicle powertrains, whereas non “drop-in” fuels require new powertrains which leads to an increase in vehicle costs.

The emissions associated with alternative fuel pathways depend very heavily on the choice of feedstock for biofuel systems and the carbon intensity of electricity for electrofuel systems. Wastes and residues (such as agricultural slurries) produce lower emissions than specifically grown energy crops. If grid electricity with a high carbon intensity is used to produce electrofuels, the WTW GHG emissions can be higher than traditional fossil fuels. To ensure the sustainability of electrofuels low carbon electricity is required. Similarly, wastes and residues have a lower land-take than energy crops, although the resource potential for these feedstocks may be limited. Electrofuel systems demonstrate very high energy yields per ha, representing an efficient use of land.

5. Perspectives

5.1. Maritime shipping

Given that the global shipping fleet is unlikely to be EEDI compliant until at least 2040 and that the GHG abatement potential from efficiency improvements alone is unlikely to provide the deep decarbonisation needed to meet the IMOs goal of reducing emissions from shipping by 50% by 2050 [36], it is clear that alternative fuels for the shipping sector are necessary. Vessel type and operational profile variability means that there is no “one-size-fits-all” solution applicable across the entire shipping sector.

Limiting fuel weight to three-times the current (diesel) equivalent, battery specific energy would need to increase approximately 7-fold to be deemed suitable for use in large vessels, which is more than likely outside the range of potential battery improvements. Niche application ferries or those with access to overnight charging may be viable sooner but this represents only a small portion of the fleet.

For vessels more than 15 years old (50% of the current global fleet), retrofitting is not an economically attractive option for shipowners [34,60]. Fully compatible drop-in fuels such as HVO or Fischer-Tropsch diesel present a low barrier pathway to reducing emissions from older vessels by making use of existing engine and fuel distribution infrastructure.

Retrofitting existing vessels to operate using multifuel engines will also play a significant role in reducing emissions from shipping, with newer vessels (15 years or younger) seemingly excellent candidates for this. Methanol presents the most attractive fuel for retrofitted vessels, as it can be stored in existing onboard fuel tanks, whereas liquefied/compressed biomethane would require additional pressurised fuel tanks to be retrofitted as well as a new engine.

For newly constructed vessels in the short to medium term, the use of compressed/liquefied biomethane or methanol in state-of-the-art multifuel engines represents a promising pathway to lessen the climate impact of shipping. Anaerobic digestion or gasification of lignocellulosic biomass followed by methanation or methanol synthesis present promising avenues to explore, offering low WTW GHG emissions and relatively low fuel costs when compared with other alternative fuels, such as electrofuels.

In the long term, a move towards zero-carbon energy carriers such as cryogenic hydrogen or ammonia will help reduce GHG emissions from the shipping sector further still. Unlike hydrogen, ammonia liquefies at higher temperatures (~34°C vs. ~253°C). Therefore, significantly less energy is required to liquify ammonia than hydrogen. ammonia can be used either in fuel cells or combustion engines for propulsion power, but further research is needed to optimise either system. If hydrogen or ammonia are produced from electrolysis, very low WTW GHG emissions may be possible, especially when considering it is expected the electricity grid will be close to net-zero emissions by 2050 [161]. Additionally, the use of electrofuels represents a more efficient use of land, producing higher yields per hectare than biofuel systems. However, significant cost reductions in electrolytic hydrogen coupled with a price on carbon are likely required to promote investment in vessels capable of using hydrogen or ammonia along with the refuelling infrastructure needed.

Vessels that operate on short-sea routes, particularly within ECAs, are viewed as good candidates for the early adoption of alternative marine fuels. These vessels often travel on fixed routes, lowering barriers to
entry as fuel supply issues are more easily mitigated. Installation of the necessary refuelling infrastructure at a limited number of ports is likely sufficient to service significant traffic and ease ship operators concerns over the security of supply.

Large, deep-sea vessels that travel between continents present greater barriers to entry as uncertainties in fuel supply chains make shipowners cautious about adopting alternatives. They can travel for months at a time before refuelling, meaning fuels with lower energy densities (such as hydrogen) would occupy significantly increased valuable space onboard and alternatives may not be available at destinations ports [29]. The improvement of energy storage technologies is seen as key to the implementation of alternative fuels in deep-sea shipping. To address concerns over fuel availability, the development of alternative refuelling infrastructure at large hub ports, such as Singapore and Rotterdam, is necessary. In the short to medium term, drop-in bio and synthetic fuels appear to be the best option for reducing emissions for deep-sea shipping, while in the longer-term cryogenic hydrogen or ammonia are promising zero-carbon energy carriers for deep seas shipping.

The cost of fuel is a significant factor in deciding to switch from conventional to alternative fuels. As seen in Section 4.2.1, the cost of all alternative fuels assessed are greater than conventional fossil fuels, with the price gap particularly evident in the shipping and aviation sectors. While costs are expected to fall due to learning curves and economies of scale, in general most consumers will only opt for alternative fuels if they are price competitive with fossil fuels. Therefore, in the short to medium term, government incentives and a higher price on carbon energy are likely to be required to encourage consumers to make the switch to low-carbon fuels.
5.2. Aviation

Analysis carried out in this paper indicates that in order to electrify both short/medium and long-haul flights, the mass of the battery to store the required amount of energy would result in a take-off weight 1.7 and 3.8 times that of the maximum allowable take-off weight of the entire aircraft respectively (Table 10). Optimistically limiting the fuel mass to three times the current value, the specific energy of battery technology would have to increase by approximately six-fold to become viable within the aviation sector, which is unlikely to occur in the short- to-medium term.

Fuels such as hydrogen (compressed/cryogenic) or biomethane (compressed/liquidified) offer superior energy-to-mass ratios compared to battery technologies. However, for short-haul flights the use of cryogenic hydrogen would account for 32% of the aircraft’s maximum allowable take-off weight, while for long-haul flights cryogenic hydrogen would account for 71% of the aircraft’s maximum allowable take-off weight. Similar results can be seen for the use of liquidified biometane, accounting for 22% and 50% of the aircraft’s maximum allowable take-off weight for short and long-haul flights respectively (Table 10). In the baseline scenario, jet fuel only accounts for 9% and 20% of the aircraft’s maximum allowable take-off weight for short and long haul flights (Table 10), meaning that the increase in fuel mass from the use of hydrogen or biometane as a fuel would significantly reduce the payload capacity of the aircraft. Furthermore, concerns over fuel storage and safety would mean that significant redesign of aircraft would be required to accommodate the pressurised storage tanks.

As the energy density requirements and limited energy storage volume for aviation make the integration of batteries and gaseous fuels especially difficult in the aviation sector, alternative liquid fuels appear to be best placed to displace the use of fossil jet fuel. Unlike the maritime sector where alcohols such as methanol can be used in modified diesel engines, alcohols are not compatible with current gas turbine technologies. Therefore, drop-in replacement bio and synthetic fuels are the only technically viable alternative fuels currently available for use in the aviation sector.

If just 50% of the global demand for jet fuel (5.5 EJ as of 2014) [13], was to be met by palm oil HVO, approximately 34 million hectares would be required to grow the required amounts of palm oil. With only approximately 17 million hectares dedicated to palm oil growth globally [162], the land area needed to grow palm oil for fuel production would need to be expanded significantly which leads to questions over sustainability. Due to the higher yields of electrofuel systems, the authors recommend that power-to-liquid electrofuels are best suited to displace large quantities of fossil jet fuel. The Westküste 100 (Table 1) project in northern Germany is an example of a potentially sustainable business model for the production of synthetic jet fuels [20]. The hydrogen required is supplied via electrolysis from an area with high volumes of difficult to manage onshore and offshore wind energy and combined with CO₂ captured from a cement production facility. An existing oil refinery is then used to produce synthetic jet fuel, which will be supplied to Hamburg airport.

Currently, the 50% maximum blend limit placed on synthetic jet fuels by the ASTM due to the lack of aromatic compounds along with wider safety concerns is a significant barrier to the large-scale uptake of synthetic jet fuels within the aviation sector. If blends of synthetic jet fuels above 50% are to be seen, rigorous testing will be required to demonstrate their airworthiness.

5.3. Haulage

The haulage sector has the lowest barriers to entry for full electrification. Analysis of the energy density and specific energy of current battery technology in this review indicates that while it is technically feasible to electrify road freight, the payload capacity of the HGV decreases by 25% for an equivalent range of a diesel fuelled HGV and 16% for a HGV with an 800 km range. However, the potential for lower operating costs seen by BEVs on a €/100 km basis combined with the fact that the majority (70%) of the global road freight fleet consists of LGVs that are amenable to electrification means that electrification is likely to play a large role in the decarbonisation of haulage. ERS systems may provide a pathway to decarbonisation for MGVs and HGVs that travel on well-defined routes along popular freight corridors. ERS technology is still in the early stages of development and haulage firms often require flexibility in their route planning; as such fuels with a greater energy density may still be required.

Biomethane has a much higher energy density than current battery technology and provides a similar range to diesel with only a 3% decrease in payload capacity caused by the extra weight associated with the fuel storage system. Both anaerobic digestion and gasification of biomass present promising pathways for the use of biomethane as a transport fuel, offering low WTG GHG emissions and lower production costs than synthetic methane produced via the power-to-gas route. A significant advantage of using biomethane as a transport fuel is that HGVs capable of running on methane are already a mature technology.

The use of hydrogen in fuel cell HGVs presents another promising pathway for the decarbonisation of haulage. The use of hydrogen in fuel cells produces no TTW emissions, with the WTG emissions associated with the carbon intensity of the electricity used in the electrolysis step. Research by McDonagh et al. has highlighted operational controls that can be put in place to reduce the carbon footprint of hydrogen in the short- to-medium term, while in the long-term plans for decarbonisation of the electricity grid mean that near zero WTG GHG emissions are possible. As seen with BEVs, the increased efficiency of fuel cell vehicles presents an opportunity to reduce operating costs. Analysis shows that if hydrogen is available at €110 per MWh, a reduction of 28% in operating costs is seen.

For hydrogen or biomethane to become attractive alternatives for haulage firms, a network of well-placed refuelling stations is essential to ensure the widespread uptake of these alternative fuels. Stakeholders are highly unlikely to switch to an alternative fuel before being assured of reliable supply. The nature of heavy-duty transport means that the requirement for refuelling infrastructure is less than for passenger transport. The placement of refuelling stations along key freight corridors would allow for significant uptake of alternative fuels within the haulage sector. The EU mandates that CNG refuelling stations should be placed approximately within 150 km of each other and that there should be one refuelling station for every 600 CNG vehicles [163].

Battery electric and fuel cell powertrains are more energy efficient than internal combustion engine drivetrains. For example, it has been estimated that direct supply of electricity for charging a battery electric vehicle offers a WTG efficiency of 73%, while using the electricity to produce hydrogen for a fuel cell vehicle delivers only delivers 22% energy efficiency, and power-to-liquid FT diesel delivers only 13% over-all efficiency [164]. While it is reasonable to assume that electrolysis and fuel cell technology will improve, there is no prospect of the hierarchy of system efficiencies between battery electric, fuel cell and internal combustion engines being reversed. This difference in overall efficiency indicates that utilising hydrogen directly wherever possible is desirable, with combustion engine technology only being used in sectors where there are no other options, such as aviation.

Euro VI emissions regulations mean that as new trucks are replaced with electric or fuel cell vehicles and make their way to the second-hand market, renewable diesels, such as HVO fuels can, be used to reduce emissions without negatively sacrificing local air quality. This is particularly applicable for developing nations, where access to battery or fuel cell vehicles may be severely limited.

The choice of alternative fuel for haulage is a lot more region specific than for the shipping or maritime sectors. Countries with an existing well-developed natural gas network and extensive sustainable biomass resource may opt for biomethane as a transport fuel in order to utilise
existing infrastructure. For nations without an existing natural gas network alternative fuels such as hydrogen may prove to be more attractive.

5.4. Future work

Future work following on from this review should include for a full multi-criteria decision analysis (MCDA) of each mode of transport to help determine a merit order of alternative fuels for each sector, taking into account the preferences of industry stakeholders. Additionally, a total cost of ownership (TCO) analysis would help fleet operators better understand the total system costs associated with switching to alternative fuels, including for infrastructural changes.

6. Conclusions

This review examined the shipping, aviation and haulage sectors and assessed a range of potential alternative fuels that could be used to decarbonise heavy-duty transport. The low energy density and specific energy of current battery technology mean that full electrification of these modes of transport faces significant challenges.

For the shipping sector, drop-in fuels present a pathway for use in older vessels where retrofitting is less economical. For retrofitted vessels or those constructed in the short-to-medium term, the use of bioethanol or methanol in advanced dual-fuel engines presents promising pathways to explore, with methanol being particularly appropriate for retrofit projects. In the longer term, zero-carbon energy carriers such as hydrogen or ammonia offer the most promising pathways to low-carbon shipping.

Aviation is particularly sensitive to weight and volume, and therefore only drop-in quality replacements for jet fuel are deemed to be technically viable to reduce emissions before 2050. These can be in the form of biofuels or synthetic fuels produced from hydrogen and carbon dioxide. Due to concerns over the ability to produce biofuels in the volumes needed by the aviation sector, it is the opinion of the authors that power-to-liquid electrofuels present the most feasible way to displace large quantities of fossil fuels from the aviation sector. It should be noted that gaining certification for alternative jet fuels is currently a major barrier that must be overcome. Additionally, maximum blend limits of up to 50% mean that without changes to the certification process, there is currently no pathway to a fully decarbonised aviation sector.

The barriers to full electrification are significantly lower for the haulage sector, with the use of battery electric delivery vehicles in the early stages of commercial development. For heavy goods vehicles that travel long distances, electric road systems may be an option to reduce emissions but it is unlikely that all roads will be electrified. Therefore, fuels with greater energy densities are likely to be required. Biomethane produced from anaerobic digestion or gasification used in natural gas heavy goods vehicles represents a mature technology pathway to reduce emissions from trucks. In the long-term, the use of hydrogen in fuel cell heavy goods vehicles serves as a pathway to low-carbon road freight, with the potential for near zero well-to-wheel greenhouse gas emissions as the electricity grid is decarbonised. However, the development of strategically placed refuelling infrastructure is key to the uptake of alternative fuels within the road freight sector.

The results of this review highlight that as the energy transition progresses, full electrification of the heavy-duty transport sector will not be feasible. Therefore, there will be a definite demand in the future for both gaseous and liquid alternative fuels.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Funding

This work was supported by Science Foundation Ireland (SFI) through the MaREI Centre for Energy, Climate and Marine under Grant no. 12/RC/2302P2 and 16/SP/3829.

References

[1] European Academies Science Advisory Council. Negative emission technologies: what role in meeting Paris agreement targets? 2018.
[2] Li FGN, Trutneyte E. Investment appraisal of cost-optimal and near-optimal pathways for the UK electricity sector transition to 2050. Appl Energy 2017;189:98–109. doi:10.1016/j.apenergy.2016.12.047.
[3] Bosetti V, Longden T. Light duty vehicle transportation and global climate policy: the importance of electric drive vehicles. Energy Policy 2013;58:209–19. doi:10.1016/j.enpol.2013.03.008.
[4] Watson SD, Lomas KJ, Buswell RA. Decarbonising domestic heating: what is the peak GB demand? Energy Policy 2019;126:533–44. doi:10.1016/j.enpol.2018.11.001.
[5] Davis SJ, Lewis NS, Shaner M, Aggarwal S, Arent D, Azevedo IL, et al. Net-zero emissions energy systems. Science 2018;360:989–993. doi:10.1126/science.aaw9793.
[6] Transport & Environment. How to decarbonise European transport by 2050. 2018. doi: 10.1017/CBO9781107415234.004.
[7] Muilolland E, Teter J, Cazzola P, McDonald Z, Ž Gallagher Ž. The long haul towards decarbonising road freight – a global assessment to 2050. Appl Energy 2018;216:678–93. doi:10.1016/J.APENERGY.2018.01.058.
[8] Transport & Environment. Roadmap to decarbonising European aviation. 2018. Transportation & Environment. How to decarbonise the UK’s freight sector by 2050. 2018.
[9] EU. Directives directive (EU) 2018/2001 of the European parliament and of the council of 11 December 2018 on the promotion of the use of energy from renewable sources (recast) (Text with EEA relevance). 2018.
[10] International Energy Agency. The future of trucks: implications for energy and the environment. 2017.
[11] Olmer N., Comer B., Roy B., Mao X., Rutherford D., Smith T., et al. Greenhouse gas emissions from global shipping, 2013–2015. 2017.
[12] International Renewable Energy Agency. Biofuels for aviation: technology briefing. 2017. doi:10.1007/978-0-12-80986-6_0012-2.
[13] International Renewable Energy Agency. Innovation outlook: advanced liquid biofuels. 2016.
[14] Malins C. What role is there for electrofuels technologies in European transport’s low carbon future? 2017.
[15] European Commission, Horizon 2020 collaborative aviation research. 2019.
[16] Bio4A | Advanced sustainable biofuels for aviation. https://www.bio4a.eu/ (Accessed January 6, 2021).
[17] flexJET | Sustainable jet fuel from flexible waste biomass http://www.flexjetproject.eu/ (Accessed January 6, 2021).
[18] REMOWFUEL - Residual soft wood conversion to high characteristics drop-in bio-FUELS - website - INEA - H2020 - 2017 - IA. http://www.renowfuel.eu/ (Accessed January 6, 2021).
[19] WenXuente100 https://www.wenxuente100.de/en/ (Accessed June 20, 2020).
[20] Bikkola J. FLASHPHS - raising the readiness of hydrogen-powered waterborne transport to a new level globally. 2019.
[21] ShipFC – Green ammonia energy system https://shipfc.eu/ (Accessed January 6, 2021).
[22] HySHIP – Hydrogen cargo vessel – NCE maritime CleanTech https://maritimecleantech.no/projects/hyship-hydrogen-cargo-vehicle/ (Accessed January 6, 2021).
[23] Daimler Trucks presents technology strategy for electrification | Daimler truck AG > innovation & sustainability >efficient & emission-free https://www.daimler-truck.com/innovation-sustainability/efficient-emission-free/mercedes-benz-geh2-fuel-cell-truck.html (Accessed December 3, 2020).
[24] Schmidt P., Weindorf W. Power-to-Liquids: potentials and perspectives for the future supply of renewable aviation fuel. 2016.
[25] Kopernikus-projekte: kopernikus-project: P2X. https://www.kopernikus-projekte.de/en/projects/p2x (Accessed December 9, 2020).
[26] CRI - Carbon recycling international. https://www.carbonrecycling.is/ (Accessed December 3, 2020).
[27] Hansson J, Månnson S, Brynolf S, Grah M. Alternative marine fuels: prospects based on multi-criteria decision analysis involving Swedish stakeholders. Biomass Bioenergy 2019;126:159–73. doi:10.1016/j.biombioe.2019.05.008.
[28] DNV GL. Comparison of alternative marine fuels. 2019.
[29] Wei H, Liu W, Chen X, Yang Q, Li J, Chen H. Renewable bio-jet fuel production for aviation: a review. Fuel 2019;254:115599. doi:10.1016/J.FUEL.2019.06.007.
[30] Baroutaji A, Wilberforce T, Ramadan M, Obali AG. Comprehensive investigation on hydrogen and fuel cell technology in the aviation and aerospace sectors. Renew Sustain Energy Rev 2019;106:31–40. doi:10.1016/J.RSER.2019.02.022.
[31] den Boer E., Aarnink S., Kleiner F., Pagendorf J. Zero emissions trucks an overview of state-of-the-art technologies and their potential. 2013.
[32] Cambridge Econometrics. Tracking into a greener future: the economic impact of decarbonizing goods vehicles in Europe. 2018.
[33] IEA Bioenergy. Biofuels for the marine shipping sector. 2017.

21
[35] Walsh C, Lazaro NJ, Traut M, Price J, Raucchi C, Sharma M, et al. Trade and trade-offs: shipping in changing climates. Mar Policy 2019;106:103537. doi:10.1016/j.marpol.2019.103537.

[36] Balcicome B, Remoroski, Skatdev L, Speirs J, Hawkes A, et al. How to decar- bonise international shipping: options for fuels, technologies and policies. Energy Convers Manag 2019;182:72–88. doi:10.1016/j.enconman.2018.12.080.

[37] EquasisThe world merchant fleet in 2017. World Merchant Fleet 2017;101.

[38] World Ocean Rev: lifetime highways of global trade. 2020.

[39] Schwartz H, Gustafsson M, Spohr J. Emission abatement in shipping – is it possible to reduce carbon dioxide emissions profitably? J Clean Prod 2020;254:120609. doi:10.1016/j.jclepro.2020.120609.

[40] International Maritime Organization. Third IMO greenhouse gas study 2014. 2014. doi:10.1007/s10584-013-9121-3.

[41] Deniz C, Zincc B. Environmental and economical assessment of alternative marine fuels. J Clean Prod 2016;113:438–49. doi:10.1016/j.jclepro.2015.11.089.

[42] Kelly EJ, Furtado F. Potential of electrification in transport. J Transp Environ Public Health 2018;5:1–12. doi:10.1080/17583004.2015.1013676.

[43] Burel A, Alvarez Jafarzadeh S, Cen, B. Scrubbers – an essential component of the life cycle assessment of triisobutane substitution. Final report 2012.

[44] Vela-García N, Bolonío D, Mosquera AM, Ortega MF, Garcia-Martínez MJ, Cannatelli L. Techno-economic analysis of the use of hydrogen in the auto- motive industry. Appl Energy 2020;268:114897. doi:10.1016/j.apenergy.2020.114897.

[45] Press releases - Rolls-Royce to test 100% sustainable aviation fuel in next generation engine demonstrator – Rolls-Royce. [Accessed December 10, 2020].

[46] Ziegelnd S, Trommler M, Schmidt P, Weinord W, Zittel W, Raksha T., et al. EU Project: Biomass fuels for low-emission transport in the EU. 2017.

[47] Scheelhaase J, Maentens S, Grimmie W, Jung M. EU ETS versus COR- SIA – a critical assessment of two approaches to limit air transport’s CO2 emissions by market-based measures. J Air Transp Manag 2018;67:55–62. doi:10.1016/j.jairtraman.2017.11.007.

[48] Air BP. Handbook of products. 2000.

[49] Chevron. Aviation fuels: technical review. 2007.

[50] Zachoske A, Schuesemann M, Orner J. High biofuel blends in aviation (HBBA) final report. 2012.

[51] Coronavirus: Aviation fuel. [Accessed December 9, 2020].

[52] JETSSCREEN: JET Fuel SCREENing and Optimization - JETSSCREEN will develop a screening and optimization platform for alternative fuels. [https://www.jetscreen-l2020.eu](https://www.jetscreen-l2020.eu) (Accessed December 9, 2020).

[53] N. Gray, J. McDonagh, R. O'Shea et al. in Advances in Applied Energy 1 (2021) 100008.
Deng C, Lin R, Kang X, Wu B, O’Shea R, Murphy JD. Improving gaseous biofuel yield from seaweed through a cascading circular bioeconomy system integrating anaerobic digestion and pyrolysis. Renew Sustain Energy Rev 2020;128:109895. doi:10.1016/j.rser.2020.109895.

Karatzas S, McMillan J, Sudder J. The potential and challenges of “drop in” biofuels. 2014.

dos Santos RG, Alencar AC. Biomass-derived syngas production via gasification process and its catalytic conversion into fuels and chemicals: a review. Int J Hydrogen Energy 2019. doi:10.1016/j.ijhydene.2019.07.133.

Rafati M, Wang I, Dayton DC, Schimmel K, Kabadi V, Shababz A. Techno-economic analysis of production of Fischer-Tropsch liquids via biomass gasification: the effects of Fischer-Tropsch catalysts and natural gas co-feeding. Energy Convers Manag 2017. doi:10.1016/j.enconman.2016.11.051.

Gallagher C, Murphy JD. What is the realistic potential for biomethane produced through gasification of indigenous Willow or imported wood chip to meet renewable energy heat targets? Appl Energy 2013;108:158–67. doi:10.1016/j.apenergy.2013.03.021.

Hoekman SK, Broch A, Robbins C, Ceniceros E, Natarajan M. Review of biodiesel composition, properties, and specifications. Renew Sustain Energy Rev 2012;16:143–69. doi:10.1016/j.rser.2011.07.143.

Low Carbon Vehicle Partnership. The renewable fuels guide 2020.

O’Shea R, Wall DM, McDonagh S, Murphy JD. The potential of power to grid to provide green gas utilising existing CO2 sources from industries, distilleries and wastewater treatment facilities. Renew Energy 2017;114:990–100. doi:10.1016/j.renene.2017.07.097.

Brynolf S, Taljegard M, Grahn M, Hansson J. Electrofuels for the transport sector: a review of production costs. Renew Sustain Energy Rev 2018;88:228–44. doi:10.1016/j.rser.2018.05.040.

Singh S, Jain S, Ps V, Tiwari AK, Nouni MR, Pandey JK, et al. Hydrogen: a sustainable fuel for future of the transport sector. Renew Sustain Energy Rev 2015;51:623–43. doi:10.1016/j.rser.2015.06.040.

Committee on Climate Change. Hydrogen in a low-carbon economy. 2018.

Sustainable Gas Institute. A greener grid: what are the options? 2017.

Greenhouse gas reporting: conversion factors 2019. GOV.UK https://www.gov.uk/government/publications/greenhouse-gas-reporting-conversion-factors-2019 (Accessed May 24, 2020).

Meller KT, Jensen TR, Aiba E, wen Li H. Hydrogen - a sustainable energy carrier. Prog Nat Sci Mater Int 2017;27:34–40. doi:10.1016/j.pnsmai.2016.12.014.

Danish Technological Institute, Methanol and hydrogen Production. 2020.

European Biofuels Technology Platform. European biofuels biofuel fact sheet dimethyl ether (DME) comparison of fuel properties. 2011.

Van Der Giesen C, Kleinj R, Kramer GJ. Energy and climate impacts of producing synthetic hydrogen fuels from CO2. Environ Sci Technol 2014;48:7111–21. doi:10.1021/es501919j.

Ulvestad A. A brief review of current lithium ion battery technology and potential solid state battery technologies. 2020.

Rivard E, Trudeau M, Zaghib K. Hydrogen storage for mobility: a review. Mater. Basel 2019;12. doi:10.3390/ma12191973.

College of the Desert. Hydrogen Properties. 2020.

Alternative fuel: G-StarTM Pro – carbon composite type 3 cylinders | Luxi Gas | O’Shea’s products/alternative fuel/g-star-pro-type-3 (Accessed May 25, 2020).

Cryogenic Cylinder for LNG for Taxis, Buses and Trucks https://www.cryofiltration.com/products-and-services/cryogenic-cylinder-for-lgn-cryogenic-cylinder-for-lgn-taxis-and-buses-and-trucks/ (Accessed May 25, 2020).

Minnenha J.J., Pratt J.W. Practical application limits of fuel cells and batteries for zero emission vehicles. 2017.

European Aviation Safety Agency. Notice of proposed amendment 2016-06 (A) fuel planning and management sub-NPA (A) aeroplanes—annex I (definitions), part ARO, part-CAT RMT.0573—15.7.2016 2020.

European Aviation Safety Agency. Type certificate data sheet no. EASA.IM.A.120 - Boeing 737. 2019.

European Aviation Safety Agency. Type certificate data sheet no. EASA.A.110 - Airbus A380. 2019.

Collins JM, McLarty D. All-electric commercial aviation with solid oxide fuel cell gas turbine-battery hybrids. Appl Energy 2020;265:117477. doi:10.1016/j.apenergy.2020.117477.

Baker H., Cornwell R., Koehler E., Patterson J. Review of low carbon technologies for heavy goods vehicles – annex 1. 2009.

Sharpe B., Muncie R. Literature review: real-world fuel consumption of heavy-duty vehicles in the united states, china, and the European union. 2015.

Weekly road fuel prices - GOV.UK https://www.gov.uk/government/statistical-data-sets/oil-and-petroleum-products-weekly-statistics (Accessed June 9, 2020).

Global 20 Ports Average Bunker Prices - Ship & Bunker https://shipdbunkerprices.com/av-global/av-g20/global-20-ports-average (Accessed June 9, 2020).

Sustainable Energy Authority of Ireland. Electricity & gas prices in Ireland. 2016. Renewable Energy and Regeneration: Biofuels and degradation of bio-dimethylether (DME) produced from various agricultural residues in Thailand. J Clean Prod 2016;134:523–31. doi:10.1016/j.jclepro.2015.10.085.

Cherubini F, Bird ND, Cowie A, Jimminger C. Biofuels–gasification of biogenic waste and bioenergy systems – issues, ranges and recommendations. Resour Conserv Recycl 2009;53:434–47. doi:10.1016/j.resconrec.2009.03.013.

Sustainable Energy Authority of Ireland. Ireland in 2019 report. 2019.

Echternor O, Sokona Y, Minx J, Farahani E, Kadner S, Seyboth K, et al. Climate change mitigation of climate change working group III contribution to the fifth assessment report of the intergovernmental panel on climate change edited by. 2014.

Korres NE, Singh A, Nizami A-S, Murphy JD. Is grass biomethane a sustainable transport biofuel? Biofuels, Bioprod Biorefin 2014;8:310–45. doi:10.1002/bbb.

Czymek-Delître MM, Chiodi A, Murphy JD, Gallachór BPO. Impact of includ- ing land-use change emissions from biofuels on meeting GHG emissions reduction targets: the example of Ireland. Clean Technol Environ Policy 2016;18:1745–58. doi:10.1007/s10098-016-1145-8.

IPCC. Climate change and land: an IPCC special report on climate change, desertification, land degradation, sustainable land management, food security, and green- house gas fluxes in terrestrial ecosystems. 2020.

Bracker J. An outline of sustainability criteria for synthetic fuels used in transport. 2017.

Defourny G, Jargioli M, Chiodi A, Deane P, Rogan F, Gallachór B PO. Climate policy zero carbon energy system pathways for Ireland consistent with the paris agreement zero carbon energy system pathways for Ireland consistent with the Paris agreement 2018. doi:10.1016/j.apenergy.2018.1464893.
[162] Pirker J, Mosnier A, Kraxner F, Havlík P, Obersteiner M. What are the limits to oil palm expansion? Glob Environ Chang 2016;40:73-81. doi:10.1016/j.gloenvcha.2016.06.007.

[163] EU. Directive 2014/94/EU of the European parliament and of the council - of 22 October 2014 - on the deployment of alternative fuels infrastructure. 2014.

[164] Transport & Environment. Roadmap to climate-friendly land freight and buses in Europe. 2017.