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Decarbonisation of Urban Freight Transport Systems through Alternative Fuels

Samuel Entwistle and Marin Marinov*

School of Engineering and Applied Science, Aston University, Birmingham, UK

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***Corresponding author:** Marin Marinov, School of Engineering and Applied Science, Aston University, Birmingham, UK

Abstract

Alternative fuels are a highly important resource for reducing emissions of greenhouse gases and other pollutants. This study includes a critical review that examines the currently available alternative fuel options including potential future developments to predict the most likely and effective options for decarbonising urban freight systems. Specifically, the introduction of this study (section 1) explains the importance of decarbonising road freight and reducing our dependence on non-renewable oil-based fuels. Section 2 involves a general review of different alternative fuel options. The production processes of different alternative fuel types are covered, as well as general information including greenhouse gas (GHG) emissions and how the fuels are used. Section 3 covers the specific benefits and challenges associated with each alternative fuel type, how they can be of use to urban freight transport systems and the potential issues that could arise when using them. Section 4 summarizes the key information about each alternative fuel type and uses it to make predictions for the possibility of future implementation in the short term, medium term, and long term.

Keywords: Road freight; Critical review, Alternative fuel; Decarbonisation; Potential; Predictions

Introduction

The transport sector is a very large and important industry and a major consumer of energy. In the European union the transport sector was responsible for 30.8% of the total energy consumption [1]. Of this, road transport was by far the largest energy consumer, making up 72.5% of the total energy consumed in the EU on average (Figure 1). In 2017, about 94% of EU transport energy needs were dependent on oil products such as gasoline, diesel, fuel oil and kerosene. Strong efforts would be needed to reduce this dependency on oil products and to reduce the emissions of greenhouse gases and air pollutants in the transport sector. These efforts may include changes to current fueling infrastructure, government policy, co-operation between different companies or other interventions. Many efforts to decarbonize transport have been made for passenger vehicles but the use of alternative fuels in heavy duty commercial vehicles is significantly smaller at this time, and strong efforts will be needed over the long term to reduce the dependency on oil products as an energy source.

The aims and objectives of this study are to analyze the different decarbonisation options for urban freight transport systems in the UK. It examines the different strengths and weaknesses of some of the available decarbonisation options, which are used to evaluate the potential future growth and implementation of different alternative fuel options. The methodology of this study includes a critical review of available sources such as journal articles, publications and studies from organizations in the field of decarbonisation and alternative energy. This study also hopes to account for the different energy needs between urban freight vehicles and passenger vehicles, as well as the different engine requirements for some alternative fuels. There are different types of freight transport including boat and rail transport. However, this study primarily focuses on road freight transport, as this makes up 90.4% of freight transport in the UK [2].

State of the Art on Alternative Fuels

This section examines different types of alternative fuels that are either being used or are in development. There are many types of alternative fuels and fuel sources, each with their own physical properties, costs, and different effects on performance or emissions.

Liquid biofuels

Liquid biofuels are a potential alternative fuel that is already seeing some use in many parts of the world. They currently account for around 2.5% of fuels used in all global transport, a number that is expected to rise by 2050 to 28% [3], making them currently one of the most important alternative fuels for road transport. In the European Union biofuels are often blended with conventional fuels, such as small amounts of biodiesel blended with conventional diesel or small amounts of bioethanol being added into gasoline. There are many different types that can also be blended with conventional fuels or used on their own such as bio-methanol, other bio-alcohols, pure/hydrotreated vegetable oils, dimethyl ether, and other organic compounds. These fuels are typically divided into three different generations. First generation biofuels are produced through common processes such as fermentation and esterification. These include bioethanol from crops rich in sugar or starch, as well as biodiesel from vegetable oils. Second generation biofuels are a broad range of products derived from non-food crops. These products can include organic parts of municipal waste and biofuels based on novel energy crops such as rapeseed or sugar beet [4]. Another example is products from agricultural or forest residues, which serve as the primary production source for the biomethane used in transport vehicles [5]. They are generally considered to be more sustainable than first-generation biofuels, however the production pathways can be more complex and more expensive. Some second and third generation biofuels are known as advanced biofuels. Third generation biofuels include biofuels derived from algae or hydrogen from biomass. This generation of fuel production pathways are still in the early research or development stages and may not yet be ready for full commercialization. Most biofuels will result in significant greenhouse gas emissions, though this will vary considerably between 26%-81% [5]. Larger effects are obtained when co-products are used or energy as well as the main products, and results are often highly dependent on the specific production pathway. Bioethanol considerably reduces the emission of nitrogen oxides (NOX), while biodiesel produces less particulate matter but can produce other emissions such as NOX emissions and aldehydes.

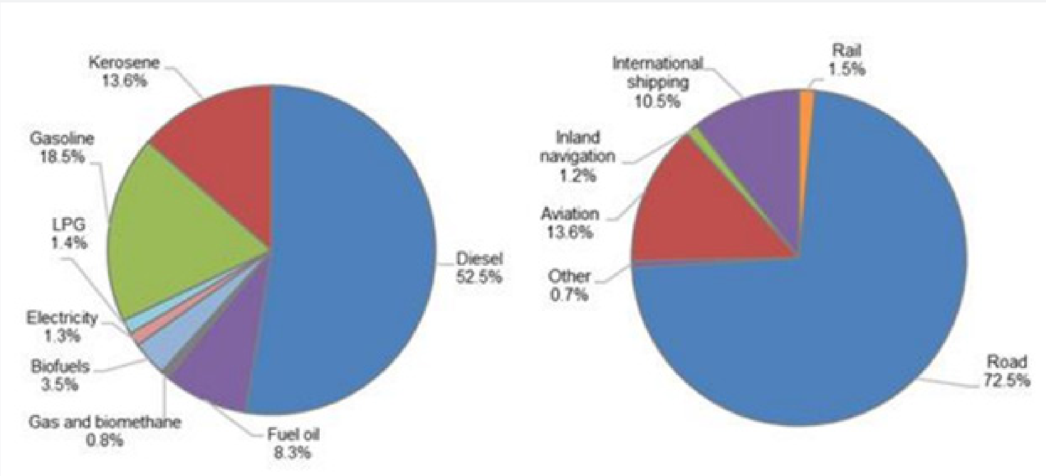

Figure 1: Share of energy demand and fuel sources for transport vehicles in the European Union in 2017 [1].

Synthetic and paraffinic fuels

Synthetic fuels are a type of advanced second-generation biofuel that can be used as a potential substitute for diesel, gasoline, or jet fuel. It comes from renewable energy sources such as biomass and other crops, as well as from gas coal or plastic waste. Paraffinic diesel fuels such as Fisher-Tropsch diesel (FT) or hydrotreated vegetable oils (HVO) can be blended into conventional fossil fuels at very high blending ratios, and they are interchangeable. This means they can be used in both existing and future vehicle engines. Other synthetic fuels such as methanol or other alcohols can be blended with gasoline to be used in current vehicle technologies, although this may need some minor adaptations of the engine to work. There are gas-to-liquid (GTL) fuels and the previously mentioned HVO fuels in the early commercial stages, with HVO using the same feedstock as biodiesel. HVO fuels are produced by hydrotreating plant oils and animal fats. Biomass-to-liquid (BTL) fuels use the same synthesis process as GTL and can use a wide range of feedstock, although production is only at the pilot level and not yet at a commercial scale. DME is also produced by the same type of process, resulting in a synthetic gas that is converted into methanol and then into dimethyl ether via dehydration of the gas. The GTL production pathway has comparable emissions to conventional diesel, HVO offers emission reductions ranging from 40-90% while BTL offers reductions ranging from 60-90% compared to conventional fossil fuels [5]. Using methanol in a combustion engine will result in emissions slightly higher than those of diesel and comparable to gasoline but blending this with renewable sources of methanol will result in an improved reduction of GHG emissions. As with many other alternative fuel types, the reduction in emissions for synthetic fuels depends heavily on the production pathway. Paraffinic fuels are free from some potentially dangerous pollutants such as Sulphur and aromatic groups. Paraffinic fuels such as GTL and Farnesane have a higher cetane rating [6], potentially leading to slightly better air

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quality due to the fuel burning more efficiently. One interesting observation of synthetic and paraffinic fuels is that they offer generally higher emission reduction levels across all emissions for heavy duty vehicles compared to light duty vehicles [5]. This could make them a very good option to consider for fueling heavy duty urban freight vehicles. Due to recent technologies some of these synthetic fuels are already at the stage where they are ready for market distribution, such as commercial HVO and GTL plants in the EU and other regions. If a plant is located near a gas field, then Carbon Capture and Storage (CCS) can be used to capture CO_2 from the production process and re-inject it into the gas field. Other technologies such as BTL are still in the pilot stage, so it is expected they will be market ready in the long term. A potentially interesting production pathway is sun-to-liquid (STL) fuels, which involves using sunlight as an energy source to produce fuel from carbon dioxide and water, though it is also possible that some other renewable energy sources such as wind power could be used instead of sunlight. This could be a good potential area of investment over the long term. For this process it may be possible for carbon dioxide to be sourced from power plants that produce it in the short term, and in the long term it could be extracted from the atmosphere for conversion into fuel when the economics are more favorable [7].

Natural gas and Biomethane

Natural gas and biomethane are another potentially important options for alternative fuels. They are both considered to be a single fuel as they are both methane gas, the difference between the two is that natural gas is derived from fossil fuel sources and biomethane can come from either biological or non-biological feedstock and renewable resources. More specifically, biological methane is produced via anaerobic digestion and gasification while non-biological methane is produced by gasification. This can come from energy crops, animal manure, sewage sludge and municipal or agricultural waste. It is also possible to produce methane synthetically through the methanisation of hydrogen gas made by electrolysis, also known as e-gas. They can be used in existing combustion engines and refueling infrastructure for liquified natural gas (LNG) and compressed natural gas (CNG). They are quieter and have cleaner emissions than gasoline or diesel while having an equivalent performance, making them a good substitute. Biomethane is a gradually increasing alternative to natural gas from fossil fuels. It can be mixed with natural gas in any ratio to be used in engines already designed for natural gas. This does mean that engines not designed for natural gas would have to be altered or replaced to use it in its gaseous state. However, natural gas and biomethane can also be used to fuel conventional combustion engines, including those in urban freight vehicles such as trucks, in the form of liquified natural gas (LNG). WTW (well-to-wheel) emission reductions for compressed natural gases lie in between gasoline and diesel, although this will depend heavily on the production pathway and the origin of the natural gas. Synthetically produced biomethane can have nearly zero emissions.

Liquified petroleum gas

Another potential alternative fuel could be in the form of Liquified Petroleum Gas (LPG), a fossil fuel that occurs naturally within natural gas and petroleum, where it is recovered and extracted during the refinery process. It is a mixture of hydrocarbon fuels, usually consisting of propane and butane with small percentages of propylene and butylene. It can be used for both light-duty and heavy-duty freight vehicles over a variety of distances, and road vehicles operating on LPG occupied 3% of the European fleet in 2015 [5]. More propane is used (40-60%) in cold weather while more butane (up to 60%) is used in warmer weather, due to it having a lower evaporation point at lower temperatures. At room temperature (20°C) LPG is in a gaseous state and becomes liquified under moderate pressures. Availability of LPG is expected to remain high as it is co-produced alongside existing natural gas and petroleum products as well as having alternative pathways. Some processes such as GTL can generate certain percentages of renewable LPG, though the amount produced will vary depending on the tuning of these processes. Despite most commonly being derived from fossil fuels, it burns with nearly no particle emissions and lower emissions of hydrocarbons, carbon monoxide and nitrogen oxides than conventional gasoline and diesel fuels. However, it has relatively small savings on emissions of greenhouse gases, and emissions of carbon dioxide are lower than gasoline but higher than those from diesel. Like most fuels, production costs will vary depending on the production pathway, and some pathways might not be ready to be scaled up to a commercial level.

Electricity

Electricity as an energy source for vehicles has already seen heavy usage over the last few decades, particularly in some commercially available electric cars and in rail transport. It can be produced from a wide variety of energy sources, including fossil fuels, wind, solar, hydroelectric, tidal, geothermal, biomass, biogas, and power from renewable waste. Usage of renewable sources increasing in more recent years while nuclear power usage remains stable and fossil fuel usage is quickly decreasing as it is replaced by more sustainable methods. Electricity use is primarily used for rail systems and is a growing trend in public transport, but it is less likely to be adopted for air or marine transport. Heavy duty vehicles and long-haul vehicles such as trucks can be partly electrified using hybrid engines, although complete electrification seems unlikely to be done in the short term. Increased electrification of transport can result in reduced GHG emissions, reduced dependence on imported fuel sources, reduced air pollution and increases in energy efficiency. Reductions in emissions would vary depending on how the electricity is produced, although this is something that urban freight companies would not have much control over. With electricity production becoming increasingly low carbon then reductions in GHG emissions overall are expected

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to increase as well, as 52% of electricity was produced by nuclear and renewable sources in 2012 and is projected to increase to 73% by 2050 [5]. Electric vehicles themselves have zero tailpipe emissions, with a potential to become nearly zero-carbon over the long term as indirect emissions from power stations are reduced through renewable and low carbon energy sources. Hybrid engines combine electrical batteries with conventional fuels and can significantly reduce emissions when compared to conventional gasoline or diesel. Electric vehicles can contribute to improvements in air quality, particularly in urban areas with many vehicles in use because electric engines do not produce harmful pollutants such as nitrogen oxides or particulates that can directly cause negative health effects. This is also true for hybrid engines when operating in electric drive mode. Electric transport has seen considerable development, several vehicle producers are making or introducing new battery powered hybrid passenger vehicles. Battery technology is continuously developing but there is still more room for improvements in battery performance and costs in the future, making it a potentially interesting option for some urban freight vehicles in the longer term.

Hydrogen fuel cells

Hydrogen is a flexible energy carrier that can be used to produce electricity for a wide variety of applications. This section will be focusing on hydrogen fuels cells, which use hydrogen to generate electricity. The most common way to produce it is through steam reforming of natural gas, a reaction which uses a catalyst and high temperatures to turn methane and water into carbon monoxide and hydrogen (also known as syngas). The carbon monoxide then reacts with water to form carbon dioxide and hydrogen. It is a well-established process with natural gas being widely available and some advance infrastructure is already in place. Some of the other processes that can be used to produce hydrogen include other thermal processes such as coal gasification, electrolytic processes such as the electrolysis of water, and photochemical processes that make use of sunlight. Electrolysis involves using electricity to split molecules of water, which can come from a variety of primary energy sources including renewables or nuclear power.

In terms of emissions, hydrogen only produces water or water vapour when burned in a fuel cell or a heat engine because it contains no carbon itself. There is however a possibility of nitrogen oxides being produced when burned in a heat engine with an excess of air in the engine, otherwise known as lean combustion. Otherwise, emissions will mostly be dependent on what primary energy source is used to make the hydrogen. Through the thermal gasification path, natural gas results in the most greenhouse gas emissions, sewage-derived biogas results in relatively lower emissions and biogas from manure can result in very low or negative emissions [5]. The electrolysis path has wildly varying results. The coal pathways have very high emissions while the pathways that use nuclear power or renewables such as wind all have similarly low to minimal GHG emissions. The energy efficiency for the production pathways can also vary considerably. The natural gas pathway results in the lowest energy consumption while biogas from sewage sludge results in the highest energy consumption [1]. For the electrolysis production pathways, the nuclear pathway has the highest energy consumption, with coal and electricity being very similar in terms of energy consumption and wind power resulting in the lowest energy consumption.

Discussion of Alternative Fuel Potentials and Challenges

With each of the alternative fuel options there are potential benefits, risks, and challenges to consider. To determine which fuels are better or worse for urban freight companies to adopt, a ranking system will be used to evaluate the potential for each of the alternative fuel options, grading them from low potential to high potential. There are many factors to consider such as emissions of greenhouse gases and other pollutants, production costs, availability of technology or resources, fuel prices, infrastructure for refueling facilities and effects on vehicle performance. Some alternative fuels may also have more specific challenges, such as fuels with different physical properties, storage requirements or other important considerations. These will all need to be accounted for when ranking each of the alternative fuel options to understand their potential for adoption and future development in the short term and long term.

Liquid biofuels

Biofuels currently account for 5% of the total fuels consumed by road transport, making them one of the more widely used types of alternative fuel [5]. However, many of the advanced second and third generation biofuels that are potentially more sustainable are still in development or not ready for full commercialization. This technology could be a potential area for growth in the long term as these more advanced fuels can have a significantly higher effect on reducing emissions. Emission reductions from biofuels are highly dependent on the production pathways and their use of co-products for energy purposes along with the main products. Specific production pathways will also have a large effect on the actual energy consumption, and these production pathways typically have a higher energy consumption per 100 km than conventional fossil fuels [5]. Many first-generation biofuels and some second-generation biofuels are produced from crops, which presents some unique challenges. Using existing cropland for biofuels will displace crops that could otherwise be used to produce food or other plant-based resources, potentially moving them to land that was previously uncultivated. One potential solution to this was discussed in a 2019 study on producing biofuels using underused urban greenspace, which suggests that approximately 10% of urban greenspace in the UK has the potential to be used to produce biofuels [8]. They estimate that this land could have the potential to supply nearly one-fifth of demand for biomass as a fuel for combined heat and power (CHP) systems by 2030 if fully utilised. Energy from this greenspace would be mainly for local electricity and heat production, but this land could potentially be used for

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growing biofuel crops for transport as well, or it could also allow agricultural land elsewhere to be used to grow more biofuel crops for transport. It is worth mentioning that some more sustainable advanced biofuels are in development that do not compete with crops for land use because they are derived from other sources such as microalgae, with some biofuel companies in the USA and Europe already being able to produce biofuels from algae on a commercial scale [3]. Producing some biofuels with crops is not a completely clean process and will result in some carbon emissions during production. While most biofuels will result in a significant reduction of GHG emissions, this rate varies considerably, and some specific production pathways can result in higher emissions than conventional fossil fuels. The EU commission [5] encourages a transition to more advanced biofuels that produce less emissions, however it also mentions that investment into advanced biofuels has decreased since 2012. Second or third generation biofuels technology could offer a potential area for growth, but this is difficult to achieve without company or government investment into these technologies. Investment is not only key for research and development for many of these advanced biofuels, but also vital for building and maintaining the required infrastructure to adopt these fuels on a commercial scale. Another factor to consider when choosing alternative fuel options is the physical properties of the fuel itself. Liquid biofuels can have different physical properties from conventional gasoline or diesel that affect how they work inside the vehicle engine, such as different heating values, lubrication properties or corrosion properties. All diesel engines since the year 2000 are currently compatible with B7 diesel which contains 7% biodiesel blended with conventional diesel, while 95% of petrol passenger cars are compatible with E10 petrol, which is blended with 10% bioethanol [5]. However, in the UK and other regions there are some older vehicles still in use that may not be compatible with E10 fuels. Putting E10 in an incompatible engine can result in corrosion and degradation to metallic or polymeric components of the engine over time. This is due to the chemical properties of bioethanol as it can be oxidized to acetic acid which lowers the pH of the fuel, and bioethanol can also cause problems when interacting with some polymers in the engine such as swelling or degradation of elastomeric materials [9]. Possible solutions to these issues could include using different metallic or polymeric materials that resist these effects in newer vehicles or adding anti-corrosion additives into fuels. Spark ignition engines are affected by how volatile certain fuels are and can also be affected by the fuels knock stability, which can be a problem because engine knocking will limit the efficiency of spark ignition engines [10]. Some biofuels when used in compression ignition engines can have a significant impact on after-treatment systems for exhaust gas. For example, biodiesel when blended with commercial fossil fuels can significantly reduce soot emissions while also leading to a slight increase in nitrogen oxide emissions [11]. Due to some these different physical properties, it may be necessary for specific engine developments to be made to accommodate them before introducing these fuels to urban freight systems. Some biofuels such as bioethanol have corrosive properties, so it may be possible to research into building engines with materials that can accommodate for the higher amount of biofuel content or adding in anti-corrosion additives to biofuels. Production costs will also need to be considered if urban freight companies want to use biofuels. They are generally more Labour intensive than conventional fossil fuels, and a lot of alternative fuels have either similar or higher production costs compared to fossil fuels. However, some biofuels can have a lower production cost depending on the production pathway. First generation biofuel costs depend more on the price of the biomass used, while costs for second generation biofuels depend more on the operating and capital costs to run the production facilities. The production costs for advanced third generation biofuels may be difficult to determine at this stage since many of them are in early stages of research and development.

Natural gas and biomethane

Natural gas and biomethane have cleaner emissions than gasoline or diesel while maintaining an equivalent performance to them. The effect on emissions will vary greatly depending on the production pathway. Natural gas on its own has less emission reduction than diesel, although it still results in considerable savings compared to gasoline. It is significantly more plentiful than crude oil with new drilling techniques having the potential to increase available resources. However, in Europe the vast majority of biomethane is used for producing heat and electricity, which significantly reduces the available amount of biomethane available for use as a transport fuel [5]. Biomethane produced through manure can have low to negative emissions, whereas biomethane made from energy crops produces more emissions in comparison but has a significantly higher production yield as energy crops produce twice the yield per hectare compared to other biofuel crops. Biomethane can have very low GHG emissions if produced through the gasification of biomass. It can have the potential for negative emissions if it is produced through feedstock or through degasification of manure because the crops/manure used would otherwise end up producing methane, another greenhouse gas, through decomposition or when used as fertilizer on fields. The highest emission reduction could be achieved by gradually adding biomethane as an additive to natural gas. Natural gas and methane can also reduce emissions for other pollutants, as they produce almost no emissions of Sulphur dioxides or particulate matter. Demand for natural gas as a fuel is set to grow in Europe, which could be supported by vehicle manufacturers [5]. However, there are some inhibiting factors such as competing fuels and the fact that biogases like biomethane are much more likely to be used for purposes outside of transport such as generating heat and electricity. One of the possible barriers for implementing these fuels is due to their gaseous nature. Conventional vehicles are designed to use liquid fuels, whereas vehicles may need to be specially designed or adapted to accommodate these gaseous fuels. They either need to be compressed or liquified to be used

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in internal combustion engines, which takes a great deal of energy to do [10]. Natural gas and biomethane can be distributed through existing natural gas pipelines in Europe or other places that have them, and it can also be delivered on tanker ships as liquified natural gas (LNG) to places that do not have existing pipelines. However, more infrastructure would be needed to have a reliable enough network of filling stations. Natural gas takes the shape of whatever container it is inside of, so special containers may need to be built to transport them if gas pipelines cannot be used, and these are more expensive than the containers used for conventional liquids such as crude oil [12]. What makes this more difficult is that compressed natural gas (CNG) and LNG fuels have different infrastructure requirements. LNG can be used in conventional combustion engines, but it needs to be handled as a cryogenic liquid, which would also necessitate the use of heavy-duty fuel transport trucks capable of handling and delivering cryogenic fluids. CNG needs to be compressed at a pressure of 200 bar, a pressure equivalent to 197.385 times the standard atmospheric pressure of earth at sea level. Handling gases at very high pressures or extremely low temperature cryogenic fluids such as LNG can be hazardous. Cryogenic fluids can cause cryogenic burns if it meets skin, and LNG has vapor that is potentially flammable if it meets an ignition source such as static electricity (Pfoser, Simmer and Schauer, 2015). This would not only make storage and transport of these fuels potentially dangerous, which could need to be considered when designing vehicles and engines to use and transport these fuels, it would also be difficult and expensive. Natural gas is the only alternative fuel that can match the energy efficiency of diesel engines when used in spark ignition engines. According to the European Commission [5] the market for biofuels has mainly developed through dual fuel systems that burn diesel fuel together with liquid methane, but more mono fuel systems are also being introduced and approved. This study also mentions that the European committee for standardization is working to improve the quality of natural gas and biomethane at filling stations by increasing the purity requirements for methane as a transport fuel. Liquified natural gas has been used to fuel combustion engines in buses, trucks and ships, and urban freight vehicles can increase the operability of commercial vehicles used in urban freight because more energy can be stored on board the vehicle. Engine technology and energy efficiency has improved since 2010 and the latest powertrain technology in CNG vehicles can reach a similar energy efficiency and performance to petrol vehicles. Optimised gas engines can improve on this further by having a higher gas compression ratio. However, these gas engines are often special developments that may not necessarily see widespread use and can still have a different engine output to equivalent engines running on conventional fuels. There are some examples of hybrid vehicles running on compressed natural gas, such as hybrid fuelled buses in Spain and Sweden [5]. The production for some of these fuels such as biogas or synthetic methane itself can have a high energy input, however this can still result in lower GHG emissions during production by using renewable energy as the primary sources. A potential area for development is using waste sources for biogas or using power-to-gas technology for generating synthetic natural gas from renewable electricity instead of fossil fuels. Production capacity can be another area for future development, as the EU is currently only using 20% of the existing capacity for LNG production [5]. Constructing new terminals for LNG or other fuels is key because vehicles need to have a reliable network of places to refill their fuel tanks to be useful. Some developments that can be made to engines themselves could include improved injection and ignition systems for improved combustion, hardware modifications to convert modern diesel engines to work with methane and sensors to monitor gas composition inside the engine. Another factor affecting production is costs. Biomethane is more expensive compared to the price of natural gas, which may make companies not want to adopt it as a more sustainable alternative. Most of these costs come from the production of biogas itself combined with the cost of upgrading the produced biogases to biomethane. Other production costs are related to those for operating and investing in production plants or costs for infrastructure such as pipelines or terminals. Companies such as those involved in urban freight distribution may also want to consider the fact that one kilogram (kg) of natural gas has 1.3 times the energy content of diesel, 1.5 times the energy content of petrol and 2.1 times that for liquified petroleum gas [5]. Natural gas contains more energy per kilogram of fuel used than other fossil fuels, making it a good alternative for freight vehicles as more energy can be stored onboard using the same mass of fuel. A dedicated natural gas vehicle can run in either CNG or LNG. They can provide reductions in carbon emissions of up to 90%, with a fuel tank that is usually larger than a diesel tank and can be stored under the chassis of the vehicle, potentially giving the vehicle more range without taking away necessary cargo space [13].

Synthetic and paraffinic fuels

Synthetic fuels are a type of advanced second-generation biofuel that comes in different forms and from a variety of different sources. Methanol is one that can be produced synthetically from syngas as well as from a range of other renewable feedstocks and is one of the most common chemicals globally, with demand and production expected to increase due to the availability of cheap shale gas [5]. However, some industries may not want to use methanol for safety reasons, as pure methanol is toxic and thus requires special precautions when handling. Methanol on its own produces GHG emissions at the same level as gasoline, though this can be reduced by blending in methanol from renewable sources. Some synthetic paraffinic fuels such as hydrotreated vegetable oils (HVO) or Fisher-Tropsch diesel (FT) can be used with existing diesel vehicle engines and in the existing infrastructure. However, blending different amounts of these fuels with diesel will result in changes to the fuel's physical properties, such as increasing or decreasing the fuel's density or altering the lubrication properties. The engine may have to be calibrated to meet regulated emission

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limits if the blended paraffinic fuel exceeds the standard density limit. Engines may have to be adapted to work with these blends due to their lower densities and worse lubrication properties, although the benefit of these paraffinic fuels is that they typically have lower emissions and better combustion properties. Gas-to-liquid (GTL) and HVO fuels are in early commercial stages with some plants active in the EU and other regions but developing a stronger demand for paraffinic fuels may be able to encourage investment into additional production plants. HVO could grow to contribute to a more significant amount of transport fuels over the longer term as a renewable fuel. Gas-to-liquid fuels come from natural gas and the production pathway has similar GHG emissions to diesel. The process is technically well established, and more large-scale plants could be built in the future thanks to technological advancements and economics becoming more favorable in recent years. The production pathways of coal-to-liquid (CTL) and biomass-to-liquid (BTL) are other potential options for synthetic fuels that have a similar production process and result in similar products. The coal pathway results in significantly higher emissions than other fossil fuel pathways. There are several plants running in China but fewer in other regions, although the use of carbon capture and storage (CCS) alongside this process can attract more interest as it would reduce the emissions resulting from the process. The BTL path is still in the pilot stage and involves the gasification of wood or similar materials. This process can result in significant reductions in emissions of 60-90%, however the problem with biomass is that it may not be suited for a traditional industrial model as it has a low energy density and potential feedstock sources may be relatively dispersed. No concrete pathway for BTL has been found so far as of 2015 [5], so further research and development is needed to find a pathway that is reliable and commercially viable. These gasification processes can be coupled with FT synthesis; however, these integrated gasification and FT plants can be complicated and expensive due to being highly energy intensive. This may also create problems when trying to scale these processes up to a commercial scale because it may not be as practical as other more simplistic production pathways. If more research is done in finding acceptable compromises or solutions to some of the practical issues with these processes, the benefits can include very low emissions alongside potential for good product quality and flexibility for possible feedstock sources. Another synthetic fuel is dimethyl ether (DME), which is produced from the same type of process used for BTL. The gasification process produces a synthetic gas, which is converted into methanol and then into DME via dehydration. It would allow for notably smaller production plants compared to GTL or LNG pathways with less investment needed. DME production is more energy intensive than conventional diesel fuel, but it can be produced easily with many plants around the world using existing coal or natural gas as feedstocks [5], the latter being the most likely feedstock for short term use. The mid-term to long-term could potentially see other renewable energy sources being used in DME or other synthetic pathways. The process is more simplistic than the FT pathway, which may help encourage more investment. CCS could be used to reduce emissions from any carbon dioxide produced during the process, though this would also make the process more expensive. The sun-to-liquid pathway is a good potential pathway over the long term as STL plants could allow for potentially unlimited feedstock by producing fuels using sunlight and significantly reduce emissions from producing certain transport fuels. It would benefit the most from being in arid areas that typically get a significant amount of sunlight for long periods of time, which means it may not be as feasible in the UK or other European countries. Plants could potentially be built in other countries so that the produced fuel could then be transported by boat, however this would add more costs and pollutant emissions to the overall production pathway. There is also the possibility that other renewable energy sources such as wind power and geothermal power could be used with synthetic pathways such as those for methanol, FT, or DME.

Liquified petroleum gas

Liquified petroleum gas (LPG) is a mixture of hydrocarbon fuels that can be extracted from natural gas and petroleum. One of the challenges for adopting it is the fact that it is gaseous at room temperature. It needs to be kept in moderately pressurized containers during transport and in the fueling station. It still needs to be kept in a pressurized container in the vehicle itself before being converted to its gaseous state in the vehicle's engine. Keeping the fuel in a pressurized container can present some potential risks of injury during transport and use if not handled correctly. It has combustion properties superior to that of liquid fuels as it readily mixes with air in the engine. It burns with nearly zero emissions of particulates and low emissions of hydrocarbons, nitrogen oxides and carbon monoxide compared to conventional fuels but has relatively small savings on GHG emissions. Dedicated modern LPG vehicles with the latest systems can already achieve lower emissions, with further potential for increased energy efficiency and cleaner exhaust emissions in the future. LPG has high knock resistance to allow more optimal combustion phasing which is important for maintaining optimum thermal efficiency within the engine [14]. LPG can sometimes contain alkenes which deplete this knock resistance and result in carbon deposits within the fuel circuit of the engine. In terms of production, LPG being a co-product of other processes means the costs will depend on what process the LPG is extracted from. A biological form of LPG known as bio-LPG originates from the production process for HVO fuels, another alternative fuel type. A large fraction of this is also used up as fuel to produce HVO. The EU commission [1] states that LPG is currently the most widely used alternative fuel, with the most mature market and a well-developed refueling infrastructure. However, it will have only a limited contribution when it comes to removing GHG emissions from transport. This could be remedied through the increased use of bio-LPG; however, the potential production is very limited and is unlikely to be utilised in the short term.

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Electricity

Electricity is an alternative energy source that is already seeing widespread use in the transport sector, particularly in rail transport, but there is room for significant development in the realm of urban freight vehicles. Heavy-duty transport and long-haul vehicles that are commonly used in urban freight systems are unlikely to be fully electrified over the short term. One of the challenges with the idea of electric urban freight transport is that freight vehicles often need to carry very heavy loads over significantly longer distances than passenger vehicles are normally expected to travel daily, and some of the electrification solutions proposed for passenger transport do not work well for freight [13]. This can be a problem, as without significant improvements in BEV technology it is unlikely for long distance urban freight vehicles to be able to function on electric power alone, and the weights they often carry will reduce the performance and range of these vehicles even further when compared to lighter passenger vehicles. It may be more likely for urban freight vehicles to be partially electrified through hybrid engine systems as this would be easier than full electrification without needing to compromise on range. It may be possible for some urban freight vehicles to be fully electrified for distribution within a relatively small area like a city where a long range is not necessary. There are some examples of these electric freight vehicles such as Amazon recently beginning to introduce fully electric delivery vans and associated charging stations to certain cities across the United States and Europe, with plans to have 10,000 of these vehicles on the road by 2022 and hoping to reach 100,000 vans by 2030 [15]. These are not the same as long haul freight vehicles such as trucks, but they have an interesting feature of supporting multiple battery sizes, meaning each vehicle could be optimised for the specific route they are travelling on.

Electric vehicles themselves, as well as hybrids when running on electric power only, produce no direct exhaust emissions. Any emissions that do exist are indirect would depend on how the electricity the vehicle is supplied with is produced. This can vary greatly between different countries and regions. In the UK, the power sector produced a large portion of its electricity from gas, with renewable wind and solar energy coming in as the second most prominent fuel source, followed by nuclear power (Figure 2). Countries may have varying levels of access to different alternative energy sources, usage of renewables is generally increasing in the UK overall each year while generation from fossil fuels such as oil or coal is decreasing. Electricity generation is projected to become more carbon neutral over the long term as fossil fuel energy sources are used less in favor of nuclear power or renewable sources. It is also expected that production plants for electricity will become more energy efficient over time as newer plants are built and older, less efficient plants may eventually be phased out of use. Even taking emissions from electricity generation into account, electric and hybrid vehicles can still make a significant contribution to removing emissions from transport and improving air quality compared with conventional diesel and gasoline. Energy efficiency is one advantage that electric powered engines can have over internal combustion engines. Well-to-wheel analysis of energy efficiency shows electric vehicles are more efficient than internal combustion engines over a wide range of primary energy sources [5]. Electric transport has undergone significant development with many vehicle producers introducing battery and hybrid vehicles. A key component in battery electric vehicles is the battery itself, as the capacity and performance of the battery (or multiple batteries in some vehicles) will determine the vehicle's range, recharge time, overall battery lifespan and the price. The current most dominant battery technology is lithium-ion batteries (LIBs), which is a mature technology used in a diverse array of electric devices including vehicles. They are considered the most promising type of battery despite their financial costs and potential concerns for availability of resources because they have a more favorable energy density and longer lifespan than other currently available battery types [13]. Ongoing research is under way for next-generation batteries such as solid-state batteries, though these are unlikely to be adopted commercially before 2030 [1]. Some potentially promising emergent technologies include quasi-solid-state batteries made from molten salts that could extend the range of electric vehicles while saving on costs and limited lithium resources [16]. Novel technologies such as this are potentially very interesting for the future of electric transport over the long term but will require significant amounts of additional research, development, and funding before they can see widespread commercial use. Battery technology for existing batteries such as LIBs have evolved in recent years with improved capacity and range for some electric passenger vehicles compared to older models. Charging systems have also improved with the addition of fast recharging stations and recharging infrastructure becoming more widespread. Putting batteries on urban freight vehicles raises concerns about decreased loading space for carrying goods and increased weight from the batteries themselves. One possible solution could be the use of overhead cables over important urban freight highways, which could reduce the need for onboard energy storage. These vehicles would also have a secondary energy source on board such as a battery, fuel cell or combustion engine to travel on parts of the road that do not have overhead cables. A study from the UK government's Foresight Future of Mobility project on decarbonizing road freight (Greening, et al., 2019) points out that these could deliver reductions in carbon emissions of up to 80%. However, it also mentions several challenges this idea faces. They would require an expensive and extensive infrastructure of overhead cables to be built, and specialized trucks need to be developed with catenary poles attached to connect to the overhead cables. The study also mentions another potential charging system involving contactless induction charging pads located in certain parts of the road. To use these a vehicle would have to have another pad attached to it that it lowers for more efficient charging, and it would need to be placed in locations where the vehicle is stationary for

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long enough to charge. Fast charging at the beginning or end of a journey could maintain the vehicles payload by reducing the need for energy storage on board the vehicle. However, much like the previously mentioned overhead cables, this solution would require a significant investment into widespread infrastructure to be effective.

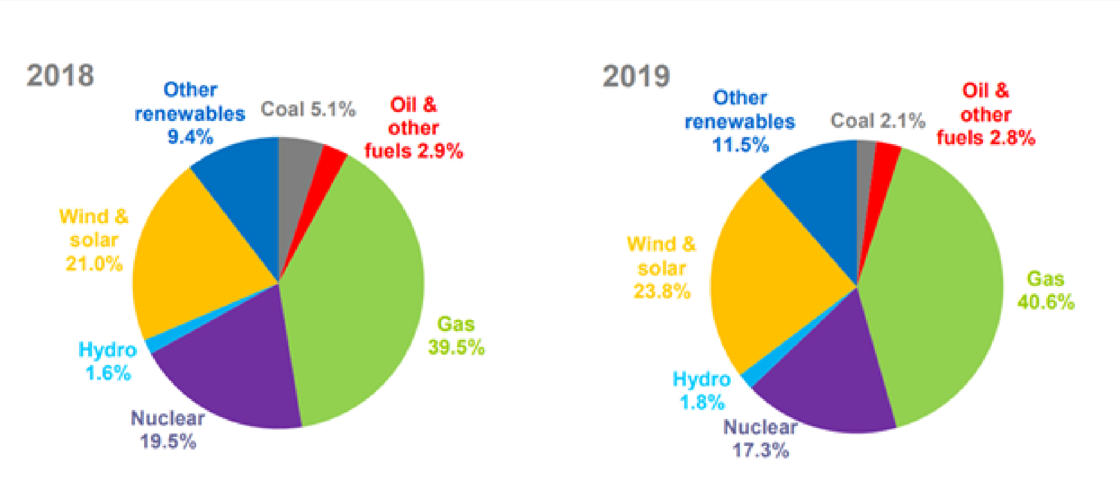

Figure 2: Summary of electricity generation by primary energy source in the UK in 2018 and 2019 [18].

Hydrogen fuel cells

One advantage of hydrogen fuel cells is that they can be produced from virtually any fuel source. The electrolysis pathway is likely to play an important role in future development as it opens opportunities for integrating renewable energy sources for production. Production paths focusing on steam methane reforming (SMR) and auto thermal reforming (ATR) are also likely to play a role in the future when combined with carbon capture and storage (CCS) to further reduce emissions. However, these technologies are currently underutilized compared to fossil fuel production paths, as 48% of the world's hydrogen production comes from natural gas and 30% comes from coal [1]. This leaves a lot of room for potential growth in the future for more sustainable options, but it means that this technology may not be the most effective option for reducing emissions in the short term. While CCS may reduce emissions significantly it is expensive and may require large scale installations to be feasible. Electrolysis is a different pathway that only represents around 4% of current hydrogen production but has the chance to become more competitive in the future. The electrolysis pathway has different technologies that are available or in development. Alkaline electrolysis is the most mature technology and has the lowest costs for investment and maintenance. Comparatively, the emerging technology of proton exchange membrane electrolysis has mostly been used commercially for small and medium applications. Production is currently at the pilot level, but it can offer several advantages over alkaline electrolysis as it can allow for more compact designs due to higher current densities and potentially allowing more flexibility. SMR may be the more cost-effective currently available production pathway for hydrogen, as electrolysis has relatively high production costs. The costs of hydrogen produced by electricity may decrease over time as renewable energy sources become less expensive. While hydrogen is already produced for industrial and refinery purposes in large quantities, hydrogen in fuel cells must be purified to a high level to remove any impurities that may impact the performance of the fuel cell. The storage and movement of hydrogen can also be an issue. It needs to be stored in tanks under very high pressures of up to 700 bars [1], making the storage and transport of this fuel expensive and potentially dangerous. The current hydrogen refueling network is still in the early stages of development, so more widespread refueling stations would need to be available to become a viable option. Hydrogen fuel cells are good for reducing emissions, but they are not necessarily the most effective as a transport fuel. On the one hand, hydrogen fuel cells have an energy density than most batteries [17]. It can provide longer ranges than BEVs while having shorter refueling times that are comparable to those for internal combustion engines. However, the fuel and fuel cells are expensive compared to other alternative fuels and the actual energy efficiency is lower than electricity when compared to existing BEVs [1]. It would be unlikely for hydrogen to be technologically or economically favorable over electricity for transport in the short term. It may have the potential to become more favorable in the long term if production costs decrease and fuel cell technology improves. Fuel cell hybrid vehicles may provide a good alternative option for vehicles such as buses, as some examples of these vehicles and locations with hydrogen filling stations already exist [17]. However, they are not anywhere near widespread enough for long haul urban freight vehicles to

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use reliably, so this option may work better for freight vehicles that only need to travel shorter distances within a city such as delivery vans [18].

Results and Evaluation

So far, this study has given a general overview of the state of different available alternative fuel options, as well as discussing some of the potential challenges and benefits associated with each of the different fuel types. This section will summarize and evaluate these fuel types while taking these previously mentioned factors into consideration to determine their potential for future usage and development. For this study, each option will be given a number from between 1 and 5, with 1 being very low potential for use in urban freight systems, 2 representing low potential, 3 representing medium potential, 4 referring to high potential and 5 would represent a very high potential for use in urban freight systems. Factors that must be considered include fuel efficiency, potential effectiveness in urban freight systems, costs, technological progress, available infrastructure, and the potential range of the fuel. Some of these alternative fuels are already in use and are a mature technology, whereas other fuel types may only see potential in the long term or are still in early stages of research and development. It is for this reason that we will consider the fuels' future potential over the short term, medium term, and long term to more accurately reflect how some of these alternative fuels and the industry itself will change over time. This study is focusing on road freight transport vehicles, which is an important distinction because some alternative fuel types may work better for some vehicles than in others. Passenger vehicles have different requirements and uses compared to freight vehicles. Liquid biofuels do have significant potential to reduce emissions depending on the production pathway. They already see common usage mostly in low amounts of biodiesel or bioethanol in most vehicles. The number of vehicles capable of supporting higher amounts of biofuel content is relatively low, as most vehicles are designed to use biofuel blends at lower percentages. They can significantly help reduce emissions in the short or medium term. However, it may be less likely that first generation biofuels will see significant usage in the long term because they are less sustainable than later generations that do not come from crops. Later generations may not be ready for production on a commercial scale in the short term or mid-term for some advanced biofuels. More advanced, more sustainable biofuels may require additional funding or government investment. Production costs are different for each pathway and generation of biofuel and depend on different factors such as feedstock prices or the operating costs of the plant itself. The engine problems caused by the physical properties of some biofuels at higher blends could be an issue for urban freight companies, and they would have to adapt their engine technology accordingly. Overall, liquid biofuels have a mixed potential overall, but they do have benefits. They can help reduce emissions when blended with some conventional fuels. Biodiesel in freight vehicles can use blends of up to 20% biodiesel content, allowing for reductions in carbon dioxide emissions of between 14% to 16% [13]. Natural gas and biomethane is potentially a very good option for urban freight vehicles, as it has a high energy density and better combustion properties than other fuels. The production pathways for biomethane can have the potential for low or even negative emissions as it has a variety of potential feedstocks. However, much of the biomethane produced often gets used for producing domestic heat or electricity, leaving less available for transport fuels. Natural gas has relatively low savings on emissions of greenhouse gases, but they can reduce emissions for other pollutants such as Sulphur dioxides or particulates. The problem with natural gas/biomethane is that it needs to be either compressed at high pressures (CNG) or liquified as a cryogenic fluid (LNG), which could potentially make it dangerous/expensive to handle and transport. The benefit of CNG or LNG is they can be used effectively in urban freight vehicles to increase range without removing cargo space. They can also match the energy efficiency of diesel engines in spark ignition engines. Overall, natural gas/biomethane is a good alternative fuel for urban freight vehicles that has potential to improve over time as developing renewable technology could allow for increased savings on GHG emissions during production and an expanded refueling infrastructure.

Synthetic fuels, much like other biofuels, come in many different types. They are typically advanced second-generation biofuels that come from renewable sources. Some of these pathways, such as BTL, are still in early stages of research and development so they will most likely not be seeing significant usage in the short term. Pathways such as the methanol or CTL may not contribute much to decarbonisation without the use of carbon capture and storage or blending in renewable sources of methanol, as these processes have comparable of higher GHG emissions when compared to gasoline. The STL pathway is unlikely to see use over the short or medium term in the UK or Europe. While it could significantly reduce emissions, it could potentially be difficult and expensive to implement if production plants are built in other countries. It could be possible for renewable energy sources to be integrated in the production pathways for some synthetic fuels such as DME or FT. Pathways involving DME or HVO fuels can take advantage of existing infrastructure and be used in current diesel vehicle engines. Differences in physical properties may cause issues when using paraffinic fuels, as blending different amounts of these fuels into conventional diesel will result in alterations to fuel density or lubrication properties. As mentioned earlier in this study, paraffinic fuels specifically may be beneficial for urban freight vehicles, as reductions in emissions are generally higher for heavy-duty vehicles than light-duty vehicles. They do not release certain pollutants such as Sulphur groups and having a higher cetane number means they burn more efficiently when used. Overall, it is difficult to determine the potential for synthetic and paraffinic fuels because there are so many different fuel types and production pathways. Some are much better or worse than others for decarbonisation and for urban freight systems. Some

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synthetic paraffinic fuels such as HVO or DME could have potential for use within existing urban freight infrastructure over the short term and beyond if differences in fuel physical properties are accounted for. Many of the other synthetic fuels are probably not going to be ready in the short term but could potentially be ready in the medium to long term. Liquified petroleum gas is a fuel that has superior combustion properties to liquid fuels as it readily mixes with air in the internal combustion engine. It does not reduce emissions of carbon dioxide by much compared to other alternative fuels, but it does burn with low emissions for particulates and other pollutants. LPG is the most widely used alternative fuel, but as it is often extracted from refining petroleum and natural gas it does not make much of an impact on reducing emissions for greenhouse gases. It has a mature market and a well-developed refueling infrastructure. It is possible for LPG to be produced from biological sources such as during the production of HVO fuels, but the potentially available production for bio-LPG is very limited, making it unlikely to see short term use. Overall, LPG certainly has benefits as a transport fuel, but until engine and bio-LPG technology improves it may not have much potential for helping towards the goal of decarbonisation in the short term or medium term. Electric vehicles are an unlikely option for urban freight vehicles in the short term. The biggest barrier is the fact that current battery technology is not powerful enough for heavy freight vehicles. The lack of range makes them a poor choice for long-haul vehicles and the addition of heavy batteries onto existing heavy-duty freight vehicles can cause a loss of loading space. Full electrification is a potentially good option for shorter range freight vehicles such as delivery vans, but for freight vehicles travelling at longer ranges it is more likely for them to use hybrid engines or other fuel types. There are potentially interesting changes to infrastructure that could be done to easily supply electricity outside of normal charging points and reduce emissions, such as overhead electricity cables or induction pads, but these changes are still in the early stages of testing and construction. These would be very expensive projects, requiring very significant investment and infrastructure development over several years before they can be reliably used. Electricity would have relatively low potential for use in road freight in the short term. However, the potential would increase over time as battery technology continuously improves and more recharging infrastructure is added. Hydrogen fuel cells can have potentially longer ranges than battery electric vehicles with shorter refueling times. Much like electricity they produce zero tailpipe emissions of greenhouse gases or pollutants. The big problems holding these back are that fuel cells are currently very expensive and have a notably lower energy efficiency than battery electric vehicles. This is combined with the general lack of availability for refueling infrastructure or currently compatible vehicles. Using fuel cell hybrid vehicles might be a good alternative to regular hybrid vehicles for providing more significant reductions on emissions, but this will still come with the problem of not having many places to refill with hydrogen unless more refueling stations are put in place (Table 1). This alternative fuel type has potentially interesting prospects over the long-term future as technology improves and expands, but it is difficult to imagine these fuel cells becoming a common part of urban freight systems in the short-term or even mid-term when more efficient and less expensive options already exist (Figure 3).

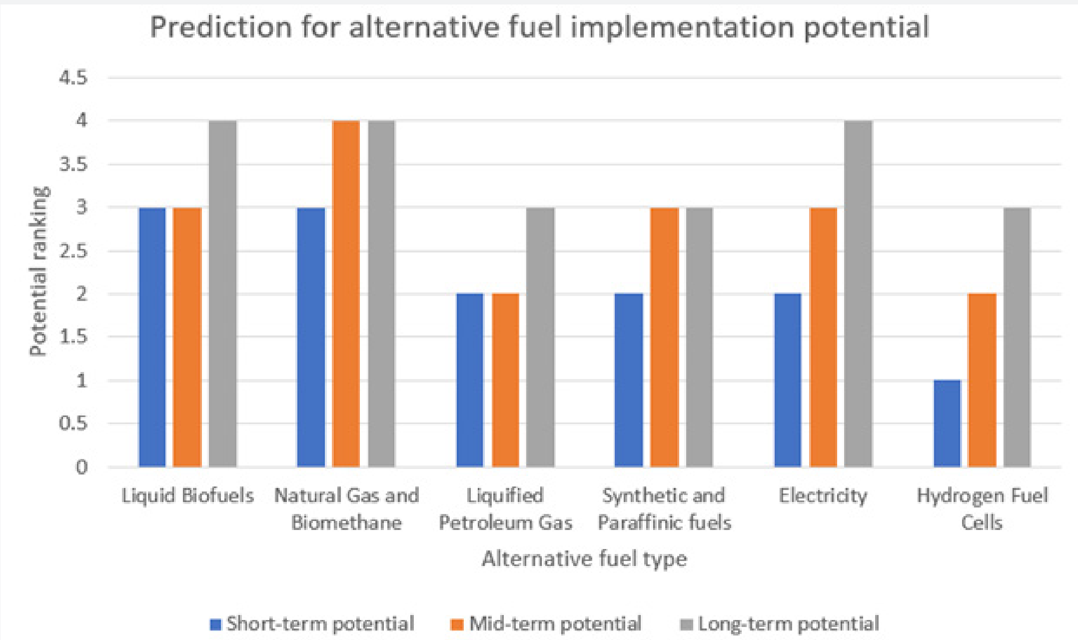

Figure 3: Graph representing predictions for the potential use and implementation of alternative fuel types over time.

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Table 1: Potential ranking of alternative fuel types.

Alternative fuel type	Short term potential (1-5)	Medium term potential (1-5)	Long term potential (1-5)
Liquid Biofuels	3	3	4
Natural Gas and Biomethane	3	4	4
Liquified Petroleum Gas	2	2	3
Synthetic and Paraffinic fuels	2	3	3
Electricity	2	3	4
Hydrogen Fuel Cells	1	2	3

These predictions indicate that liquid biofuels and natural gas/biomethane are likely to have higher potential for use over the short term. This is because they can both use existing vehicles and infrastructure to reduce emissions or provide more efficient fuels for current urban freight vehicles. These would increase slightly over the medium and long terms as more sustainable liquid biofuels can be used instead of older first-generation biofuels, while biomethane could potentially save emissions if it becomes more widely used over the longer term for transport instead of natural gas. LPG is probably less likely to be adopted for freight decarbonisation over the short and medium terms because it only has very minor savings on emissions compared to other fuels. This may increase in the long term if bio-LPG becomes more widely available, currently production of bio-LPG is very limited. Some synthetic and paraffinic fuels such as DME or HVO could see potential use over the short and medium term by using existing infrastructure. However, other more advanced synthetic technologies are going to take longer to be market ready than others. Full electrification is unlikely to occur over the short term or medium term without significant improvements in battery technology. Urban freight systems might be able to be fully electrified in the long term with sufficient infrastructure put in place with significant investment from companies or governments. Electrification can occur in the short and medium terms on a smaller scale or through hybrid vehicles. Hydrogen technology is unlikely to be used in the short term and medium term due to significant costs, poor energy efficiency and an infrastructure that is not yet at a scale where it could support long distance freight. May have potential to be used on a small scale or in the long term with significant reductions in costs and expanded infrastructure.

It is important to mention that there is no single "best" option for alternative fuel systems. Each one has their advantages and disadvantages. While some alternative fuel or energy sources may not be suited to use in urban freight vehicles, they could still be used for decarbonisation in other areas. Investing in fuels and energy sources that are expected to become more important over the long term is crucial for ensuring they have the necessary infrastructure to be viable. It is equally important to invest in fuels with greater short term or medium-term potential as well if we are to meet our goals for decarbonisation, as these can still contribute to reducing emissions over time. It is highly likely that the solution to fuel/resource demands and GHG/pollutant emissions will include a mixture of alternative fuels from many different primary energy sources.

Conclusion

In conclusion, this study has examined some of the available alternative fuel options and looked at the specific benefits and challenges associated with them. Taking this information into account, predictions were made about which options could have the most potential to see significant use for urban freight transport systems in the short term, medium term, and long term. Liquid biofuels were predicted to have a medium potential in the short term and medium term, and then a high potential in the long term. Natural gas was predicted to have a medium potential in the short term and a high potential for the medium term and long term. LPG was predicted to have a low potential in the short and medium term, then a medium potential in the long term. Synthetic and paraffinic fuels were predicted to have a low potential in the short term, and a medium potential in the medium term and long term. Electricity was predicted to have a low potential in the short term, a medium potential in the medium term and a high potential in the long term. Hydrogen fuel cells were predicted to have a very low potential in the short term, a low potential in the medium term and a medium potential in the long term.

Future Research

For many of the predictions that were given a low or very low potential they may have needed very significant investments and technological/economic improvements before they could be viable for urban freight systems. It is possible that more of these alternative fuel options will become feasible over time as technology improves, infrastructure expands, and economics end up becoming more favorable. This study looked at different categories of alternative fuel sources overall. Future research could involve focusing on more specific technologies within certain alternative fuel categories and evaluating them individually.

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