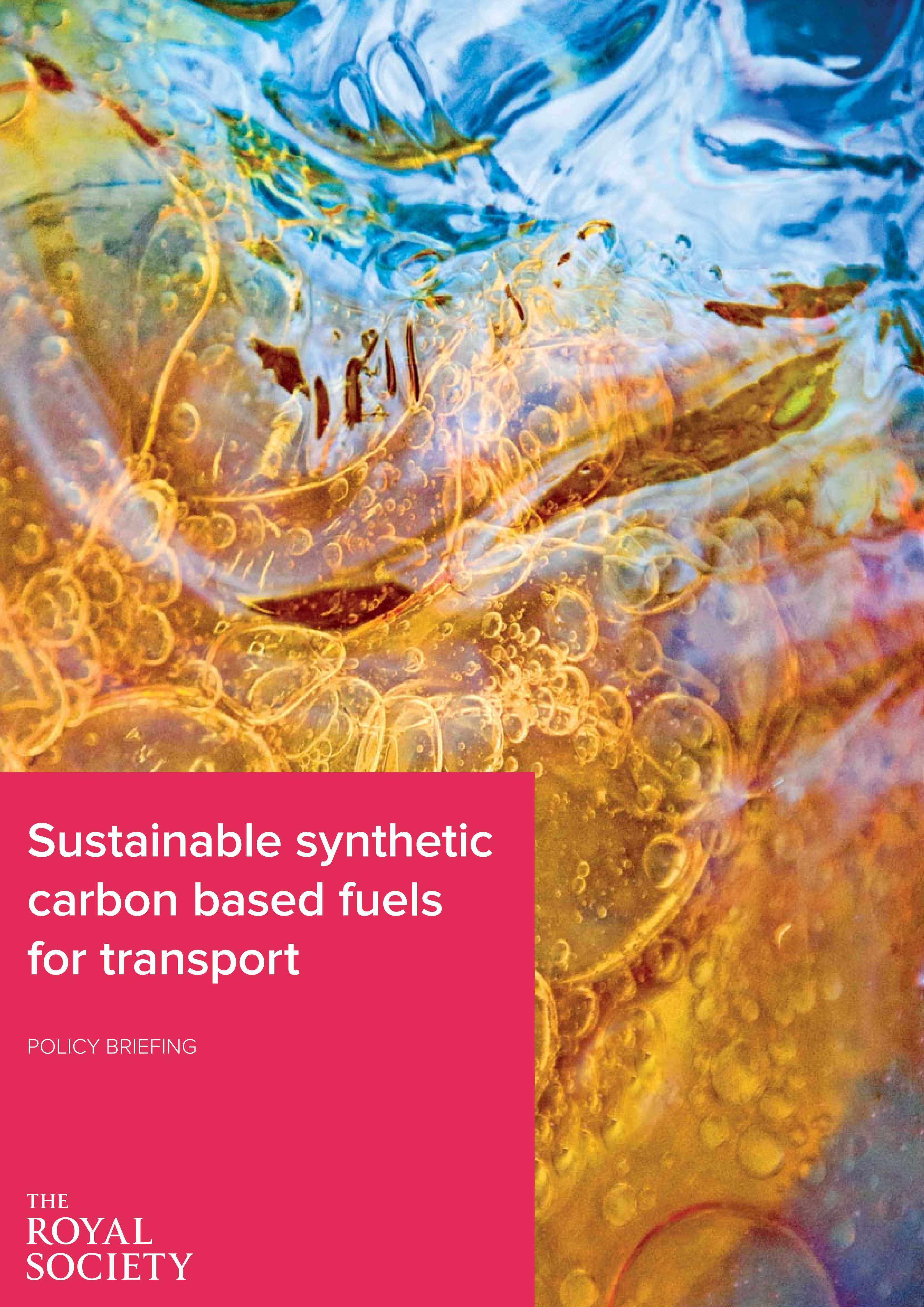

Sustainable synthetic carbon based fuels for transport

POLICY BRIEFING

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Policy briefing

Politics and science frequently move on vastly different timescales. A policymaker seeking evidence on a new policy will often need the answer in weeks or months, while it takes years to design and undertake the research to rigorously address a new policy question. The value of an extended investigation into a topic cannot be understated, but when this is not possible good evidence is better than none.

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Sustainable synthetic carbon based fuels for transport: Policy briefing
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Contents

Executive summary

The need to achieve net-zero greenhouse gas emissions from all human activities has never been clearer. One area requiring urgent action is the transition from the use of fossil fuels for transport. Whilst the decarbonisation of electricity is progressing and many transport modes can feasibly be electrified, some transport modes, such as heavy-duty vehicles, aircraft and shipping will require different technological options. The cost, volume and energy density of alternative fuels are of critical importance.

This briefing considers the science allowing a pathway to achieving this transition, through the sustainable production and use of carbon based synthetic fuels. Synthetic fuels can be manufactured, via chemical conversion processes from 'defossilised' carbon dioxide sources such as point source capture from the exhausts of industrial processes, direct capture from air or from biological sources. Whilst synthetic fuels emit carbon dioxide when burnt, this report demonstrates that synthetic fuels could, in the medium to long term (5 to 10+ years), displace fossil fuels. However, a full life cycle assessment of their manufacture has yet to be evaluated in depth.

Two methods of making carbon based sustainable synthetic fuels are explored in this briefing (Figure 1);

i. electro fuels (efuels) made using captured carbon dioxide in a reaction with hydrogen, generated by the electrolysis of water, and

ii. synthetic biofuels made through the chemical or thermal treatment of biomass or biofuels.

The background technology to produce synthetic fuels is well known and used at scale (eg Fischer Tropsch synthesis using carbon monoxide). However, these existing processes use fossil carbon sources and new technologies and further innovation will be required to enable non-fossil carbon dioxide sources to be used.

The advantages of sustainable synthetic fuels are:

- They can be manufactured as 'drop in' replacements for fossil jet fuel, diesel and fuel oil
- Both the volume and energy density of synthetic fuels are similar to existing fuels
- They can be designed to burn cleanly, reducing other pollutants associated with fossil fuel use, such as particulates and nitrogen oxides
- Existing infrastructure can be utilised for distribution, storage and delivery to the vehicle

and the disadvantages are:

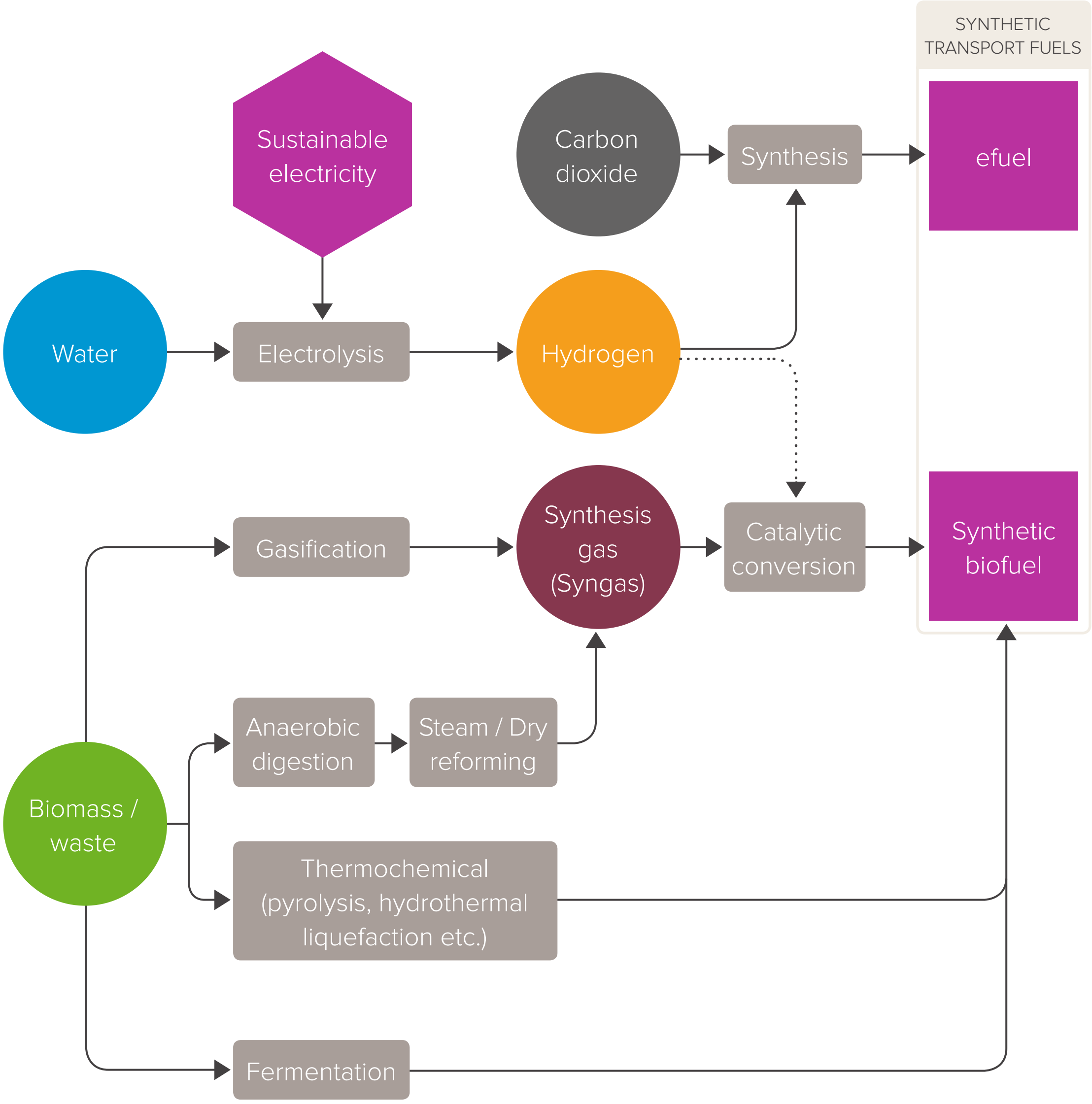
- Synthetic fuels from both biomass and carbon dioxide are currently more expensive than fossil fuels, for example around €4.50/litre for diesel equivalent efuel and around €1/litre petrol equivalent biofuel. Innovation in each process stage has the potential to reduce these costs in the future to enable production and scale up to defossilise the current and growing future transport demands. Estimated future costs vary greatly but range from 60 cents to €1.50 per litre for diesel equivalent efuel by 2050.
- The energy losses from manufacturing and using synthetic fuels are high due to the many processes involved. However, this might be justified where electrical propulsion is not practical and renewable electricity is cheap and plentiful.

Further scientific research is required in: improving the fundamental understanding of catalysis; the need to produce cheap green hydrogen at scale; and developing sources of competitively priced low-carbon energy are key to the development of synthetic efuels and biofuels.

With further development, synthetic fuels could offer a pathway to achieving net-zero carbon for transport in the long term. The UK has the research skills and capacity to improve many of these process steps such as in catalysis and biotechnology, and to provide a further area of UK leadership in low-carbon energy.

FIGURE 1

Routes to carbon based sustainable liquid synthetic fuels.



Introduction

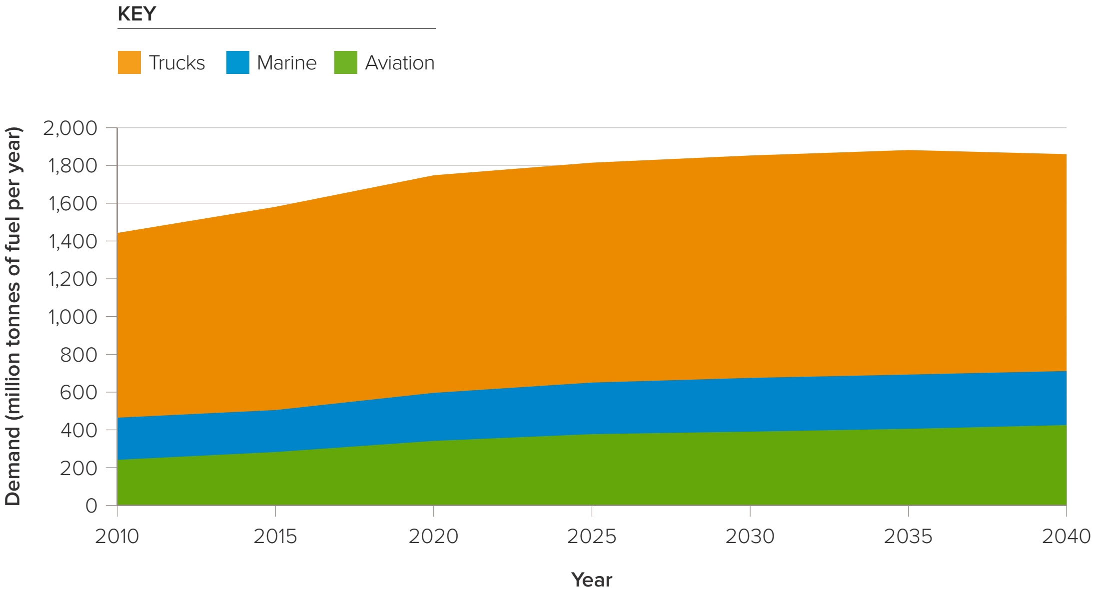
Forecasts to 2040 predict that global energy demand will increase for all modes of transport, including these 'hard to reach' areas.

Considerable progress towards the decarbonisation of transport is promised through the electrification of passenger vehicles. However, there will be transport sectors such as heavy-duty vehicles, aviation and shipping, for which electrification may not be appropriate due to cost, volume and energy density. Research into the electrification of long distance transport vehicles is continuing[1], but for the medium term alternative liquid fuels are required that are consistent with the need to decrease the dependency on fossil fuels.

Forecasts to 2040 predict that global energy demand will increase for all modes of transport, including these 'hard to reach' areas (Figure 2). The decarbonisation of transport will require the replacement of energy dense fossil fuels (diesel, aviation, bunker fuel) with low or net-zero carbon, sustainable synthetic fuels.

FIGURE 2

Forecast global energy demand for transport fuels[2].



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[1] Schäfer AW *et al*. 2018 Technological, economic and environmental prospects of all-electric aircraft. Nature Energy, 4, 160-166. (doi: 10.1038/s41560-018-0294-x).

[2] BP. 2019 Energy Outlook. See https://www.bp.com/content/dam/bp/business-sites/en/global/corporate/pdfs/energy-economics/energy-outlook/bp-energy-outlook-2019.pdf (accessed 17 April 2019).

BOX 1

Scope of this briefing

Synthetic fuels: Carbon based liquid fuels manufactured, via chemical conversion processes, from a carbon source such as coal, carbon dioxide, natural gas, biogas or biomass.
This includes established conventional fossil-based processes (see Box 2).

1. Electrofuels (efuels)

These are synthetic fuels manufactured using captured carbon dioxide or carbon monoxide together with low-carbon hydrogen. They are termed electro- or efuels because the hydrogen is obtained from sustainable electricity sources eg wind, solar and nuclear power.

2. Synthetic biofuels

In this report, these are defined as fuels synthesised from biomass or waste or biofuels using chemical or thermal processes. The production of fuels using biomass and only biological processes are outside the scope of this briefing (for example, bioethanol produced through fermentation of sugars).

Synthetic fuels could also have a role in the pathway to decarbonising heat, energy storage and the manufacture of chemical feedstocks, however these applications are not considered in this briefing. Further, it should be noted that other non-carbon fuels could be made using sustainable electricity, for example hydrogen and ammonia. Their production and use is not considered in this briefing but have been discussed in other Royal Society policy briefings[3,4].

Production routes to synthetic fuels, such as the Fischer Tropsch conversion and methanol synthesis, are well known and are currently applied commercially to fossil-carbon sources such as coal and natural gas (Box 2).

There is potential for these and other new production routes to contribute to the future decarbonisation of the transport sector, as a direct route from power (electricity) to liquid. For this to happen:

- The carbon must be derived from sustainable non-fossil sources such as biomass, direct air capture or industrial exhaust gasses.
- The energy input required for chemical conversion should be from sustainable electricity and/or low-carbon hydrogen (green hydrogen).

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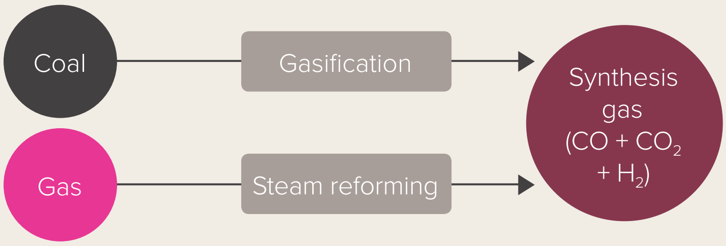
3. The Royal Society. [in press] Potential roles of ammonia in a carbon free future: Fertiliser, energy store and fuel.
4. The Royal Society. 2018 Options for producing low-carbon hydrogen at scale: Policy Briefing. See https://royalsociety.org/-/media/policy/projects/hydrogen-production/energy-briefing-green-hydrogen.pdf (accessed 17 April 2019).

BOX 2

Current production of synthetic fuels

Synthetic liquid fuels have been manufactured for many decades through a) methanol synthesis and b) the Fischer Tropsch process, both using fossil sources of carbon. For both processes, the starting point is the conversion of the fossil fuel (coal, oil or natural gas) to synthesis gas, which is a mixture of carbon monoxide, carbon dioxide and hydrogen.



a) Methanol Synthesis

Methanol is produced by reacting the synthesis gas at relatively high pressure and temperature using a copper catalyst. This process has been operated globally for over 60 years and produces more than 70 million tonnes/year. Methanol can then be converted over a catalyst to produce synthetic liquid fuel such as petrol. This process is operated at a commercial scale. Alternatively reacting methanol over a catalyst to make alkenes, a process that is currently operated commercially, and the products can be used as precursors to synthetic liquid fuels.

b) Fischer Tropsch

To use carbon dioxide in the established Fischer Tropsch (FT) synthesis, it is converted to carbon monoxide by reaction with hydrogen using the ‘reverse water gas shift’ reaction:

The carbon monoxide and hydrogen are then reacted over either cobalt or iron catalysts to produce a range of hydrocarbons (light gases C1-C4, petrol C5 – C9, kerosene C10 – C11, diesel C12+). The full product spectrum can be used in the energy and transport sectors following separation. The initial impetus for this process was to produce sulphur-free diesel but it is now used to exploit very low-cost natural gas, with the added benefit that the diesel is sulphur-free.

Modifying the industrial methanol synthesis and Fischer Tropsch reactions to operate with carbon dioxide and hydrogen will require innovation and research.

Synthetic biofuels and efuels have the potential to reduce greenhouse gas emissions through the creation of a sustainable carbon cycle (Figure 3).

a. With biofuels, the carbon is cycled from the atmosphere, through the growth of plants, converting into fuel, burning in an engine, releasing the carbon into the atmosphere again. It should be noted that the timescale of this biological carbon cycle is dependent upon the growth rate of the feedstock, for example, the time taken to produce sugar cane residue versus forestry residue.

b. With efuels, captured carbon is converted into fuel and then burnt in an engine, releasing the carbon back into the atmosphere. For efuels, the origin of the carbon dioxide will change the carbon reduction benefit, for example whether it came from an otherwise unavoidable carbon dioxide by-product or from a fossil fuel flue.

The recycling of carbon, shown in Figure 3, would contribute to meeting net-zero targets through 'defossilisation'; replacing the need to extract and burn fossil fuels, whilst creating a pathway to the longer-term options that would completely remove carbon dioxide emissions. It also reduces the extent of carbon dioxide capture and storage (CCS) required to meet net-zero carbon emissions.

The recycling of carbon would contribute to meeting net-zero targets through 'defossilisation'.

FIGURE 3

A sustainable carbon cycle utilising biomass and carbon dioxide.

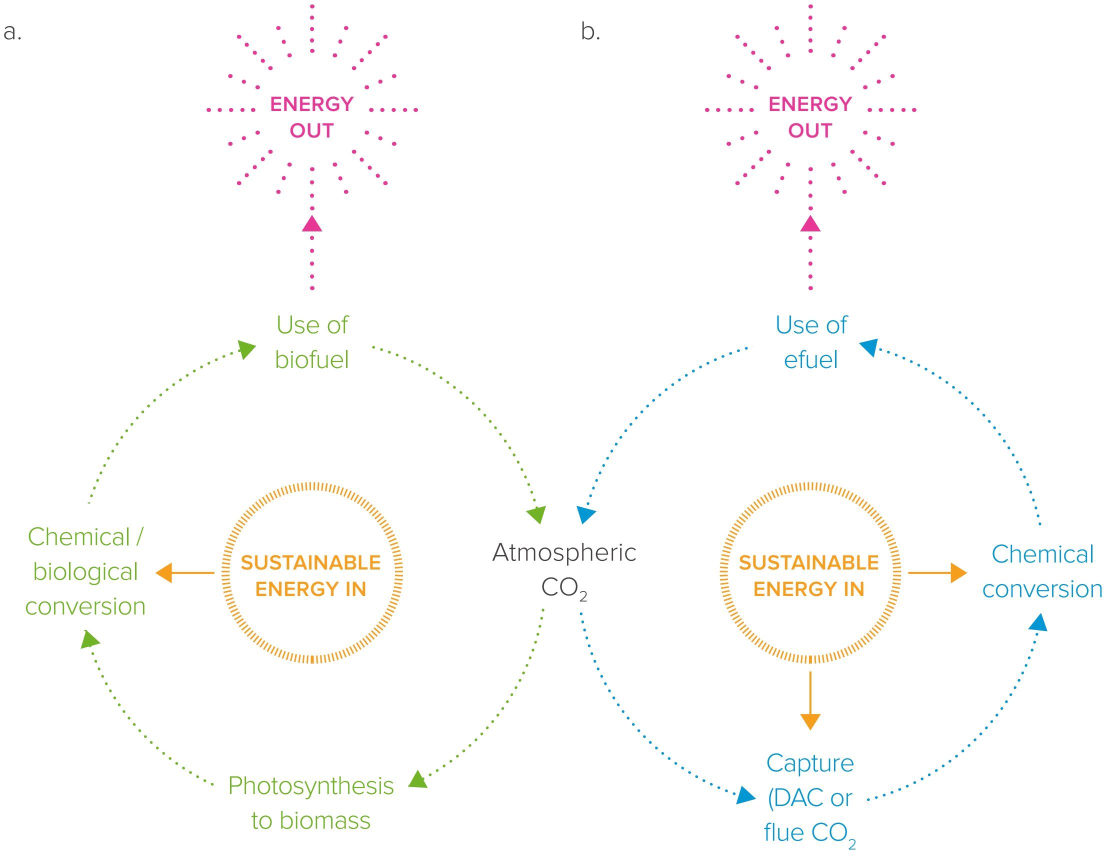
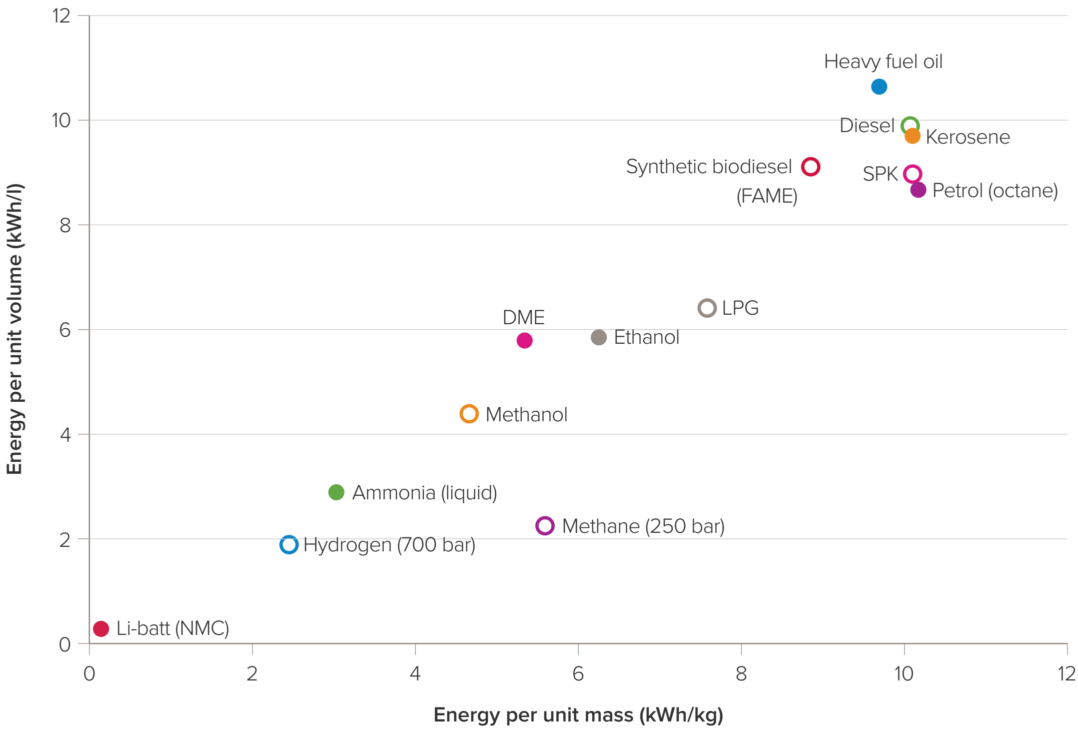


FIGURE 4

Specific energy and energy density of a range of fuel options, taking into account typical tank weights (lower heating value).



SPK Synthetic Paraffinic Kerosene; **Li-batt(NMC)** Lithium Nickel Manganese Cobalt Oxide Battery; **LPG** Liquid Petroleum Gas; **DME** Dimethyl Ether, **FAME** Fatty Acid Methyl Esters

Decarbonising options for transport modes

Fossil fuels are used across all transport modes, in part due to their high energy density (Figure 4). Potential alternative low-carbon energy vectors, such as lithium batteries, have a much lower energy density than fossil fuels and their suitability is dependent on the energy demands of the journey.

Table 1 illustrates the compatibility between different fuels/energy sources and vehicle/duty cycle types along with the level of challenge for fuel distribution and refuelling infrastructure. It shows the limited low-carbon options available to transport modes with high journey energy requirements (heavy-duty truck, marine and aviation).

TABLE 1

Comparisons and suitability of different energy sources and vehicle types based on energy density infrastructure requirements.

KEY

🟩 Fully compatible 🟨 Minor restrictions 🟧 Major restrictions 🟥 Severe restrictions

⛽ Refuelling infrastructure challenge ∫ Distribution infrastructure challenge

Vehicle and duty cycle compatibility		Synthetic efuels	Biomethane	Hydrogen	Electricity	% Contribution to UK 2017 total CO_2[5]
City car		🟩	🟩 CNG	🟩	🟩	7
Long distance car		🟩	🟩 CNG	🟩	🟨	10
Urban van		🟩	🟩 CNG	🟩	🟩	2
Heavy-duty truck		🟩	🟨 LNG	🟧	🟧	5
Aviation	Short haul	🟩	🟧	🟧	🟧	9
	Long haul	🟩	🟥	🟥	🟥	
Marine	Short journey	🟩	🟨 LNG	🟨	🟩	4
	Long journey	🟩	🟨 LNG	🟧	🟥	
Distribution and refuelling challenge		🟩 ∫ 🟩 ⛽	🟨 ∫ 🟨 ⛽	🟥 ∫ 🟧 ⛽	🟧 ∫ 🟧 ⛽	

CNG (Compressed Natural Gas); **LNG** (Liquefied Natural Gas)

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5. UK Department for Business, Energy and Industrial Strategy. 2017 UK emissions data selector, National Atmospheric Emissions Inventory. See https://naei.beis.gov.uk/data/data-selector-results?q=121202 (accessed 17 April 2019).

Heavy-duty road transport fuels

The fuel demands of road vehicles differ depending upon the distance covered, journey type and load carried. Longer journeys and heavy loads require a high energy density source to avoid taking up vehicle space and adding to the weight of the vehicle. Heavy-duty freight applications are particularly challenging for battery technology due to the size and weight of the battery packs compared to liquid fuels. Currently electric applications in the commercial vehicle sector are limited to vans and light goods vehicles.

In 2017, emissions from heavy-duty road transport made up around 5% of all UK carbon dioxide emissions[6]. EU legislation has been announced which sets targets to reduce heavy-duty vehicle carbon dioxide emission to 15% below 2019 values by 2025[7]. In parallel, a growing understanding of the influence of air quality on health has led to activity in all sectors to reduce emissions of pollutants such as particulates and nitrogen oxides (NO_x).

Solutions, other than synthetic fuels, include using natural gas for road transport, which results in small reductions in greenhouse gas emissions[8]. Biomethane gives greater carbon dioxide reductions, but is currently used in a relatively small proportion of the heavy-duty vehicle sector. The use of hydrogen in fuel cells offers comparable tank filling times to liquid fuels and the potential for large greenhouse gas emissions reductions. Current barriers to hydrogen include the cost of generating low-carbon hydrogen, the high vehicle costs and limited hydrogen refuelling infrastructure, poor energy to volume density and higher costs anticipated for heavy-duty applications due to more stringent durability requirements.

Marine transport fuels

The world's shipping traffic currently represents 2.6% of global carbon dioxide emissions (2015) and the International Maritime Organisation (IMO) states that shipping emissions could grow between 50% and 250% by 2050[9]. The decarbonisation of maritime transport is challenging due to the distances travelled, loads carried and the long lifetime of ships.

A variety of approaches have been developed to reduce the carbon intensity of shipping, such as improving the energy efficiency of vessels, integrating exhaust gas treatment and waste heat recovery, but these alone cannot decarbonise shipping[10].

Alternative fuel solutions, aside from synthetic fuels, include the substitution of heavy fuel oil and marine diesel oil by liquid natural gas. This has the potential for small reductions in greenhouse gas emissions, but any benefit might be lost through methane leakages[11]. The risk of methane leakage can

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6. *Op.cit.*, note 5
7. European Commission. 2018 Climate Action, Reducing CO2 emissions from heavy-duty vehicles. See https://ec.europa.eu/clima/policies/transport/vehicles/heavy_en (accessed 17 April 2019).
8. Sustainable Gas Institute, Imperial College London. 2019 Can Natural Gas Reduce Emissions from Transport? Heavy Goods Vehicles and Shipping, White Paper. See https://www.sustainablegasinstitute.org/wp-content/uploads/2019/02/SGI-can-natural-gas-reduce-emissions-from-transport-WP4.pdf (accessed 17 April 2019).
9. International Council on Clean Transportation. 2017 Greenhouse Gas Emissions from Global Shipping, 2013–2015. See https://www.theicct.org/sites/default/files/publications/Global-shipping-GHG-emissions-2013-2015_ICCT-Report_17102017_vF.pdf (accessed 17 April 2019).
10. International Council on Clean Transportation. 2011 Reducing Greenhouse Gas Emissions from Ships: Cost effectives of available options. See https://theicct.org/sites/default/files/publications/ICCT_GHGfromships_jun2011.pdf (accessed 17 April 2019).
11. European Academies Science Advisory Council. 2019 Decarbonisation of transport: options and challenges. See https://easac.eu/fileadmin/PDF_s/reports_statements/Decarbonisation_of_Tansport/EASAC_Decarbonisation_of_Transport_FINAL_March_2019.pdf (accessed 13 June 2019).

also constrain techniques for addressing other pollutants[12].

Hydrogen and in particular ammonia have the potential to address carbon emissions[13], however the technology and supply chains for hydrogen are not currently commercially developed, with higher costs than some competing options[14]. The maritime industry has already identified the significant potential for ammonia as a green fuel for shipping, noting its ease of storage, existing networks and flexible use in both fuel cells and combustion engines[15].

Aviation fuels

In 2018, domestic and international aviation emitted 2.4% of global energy-related carbon dioxide emissions and is experiencing rapid growth[16], with the International Air Transport Association (IATA) forecasting a doubling of global passenger numbers to 8.2 billion by 2037[17].

To tackle the carbon emissions of new aircraft, dramatic improvements in energy efficiency of between 16% and 40% have been achieved[18]. A range of other advances is envisaged to achieve the target of 75% carbon dioxide overall reduction[19]. However, these developments are unlikely to be sufficient, which has led to alternative propulsion technologies being considered, including electrification. This will be contingent on achieving battery energy densities significantly beyond those achievable today[20].

The range, speed, and need to accommodate freight capacity required for civil aviation requires a highly energy dense fuel such as kerosene. Other liquid fuels with lower carbon intensities exist and can be utilised in aviation for example liquefied natural gas (LNG), however many present significant challenges in for example containment, safety and the need to develop new fuel handling arrangements[21].

Several non-fossil fuels exist for aviation, including aviation biofuel blends. For example, Synthetic Paraffinic Kerosene (SPK) made from bio-derived oils, can be used as a drop-in fuel for commercial aircraft at a blend of up to 50% with traditional kerosene. There are agreed non-fossil fuel standards covering the technical suitability of jet fuel and five technical production pathways have been certified[22]. With the increasing pace and degree of 'defossilisation' of aviation fuel, it is possible aircraft will be required to operate on higher percentage blends of alternative fuels than currently allowed for in the existing standards.

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12. *Op. cit.*, note 8
13. *Op. cit.*, note 3
14. *Op. cit.*, note 4
15. *Op. cit.*, note 3
16. International Air Transport Association. 2018 Fact sheet: climate change and CORSIA. See https://www.iata.org/pressroom/facts_figures/fact_sheets/Documents/fact-sheet-climate-change.pdf (accessed 14 June 2019).
17. International Air Transport Association. 2019 20-year passenger forecast. See https://www.iata.org/publications/store/Pages/20-year-passenger-forecast.aspx (accessed 14 June 2019).
18. Sustainable Aviation. 2018 Sustainable Aviation CO2 Roadmap. See https://www.sustainableaviation.co.uk/wp-content/uploads/2018/06/FINAL___SA_Roadmap_2016.pdf (accessed 17 April 2019).
19. Advisory Council for Aviation Research and Innovation in Europe (ACARE) Flightpath 2050
20. Roland Berger. 2017 Aircraft Electrical Propulsion – The Next Chapter of Aviation? See https://www.rolandberger.com/en/Publications/New-developments-in-aircraft-electrical-propulsion-(CH).html (accessed 17 April 2019).
21. Roberts R, Nuzum SR, Wolff M. 2015 Liquefied Natural Gas as the Next Aviation Fuel. Propulsion and Energy Forum. (doi: 10.2514/6.2015-4247).
22. ASTM International. Standard Specification for Aviation Turbine Fuel Containing Synthesized Hydrocarbons – ASTM D7566. See https://www.astm.org/Standards/D7566.htm (accessed 17 April 2019).

Synthetic electrofuels

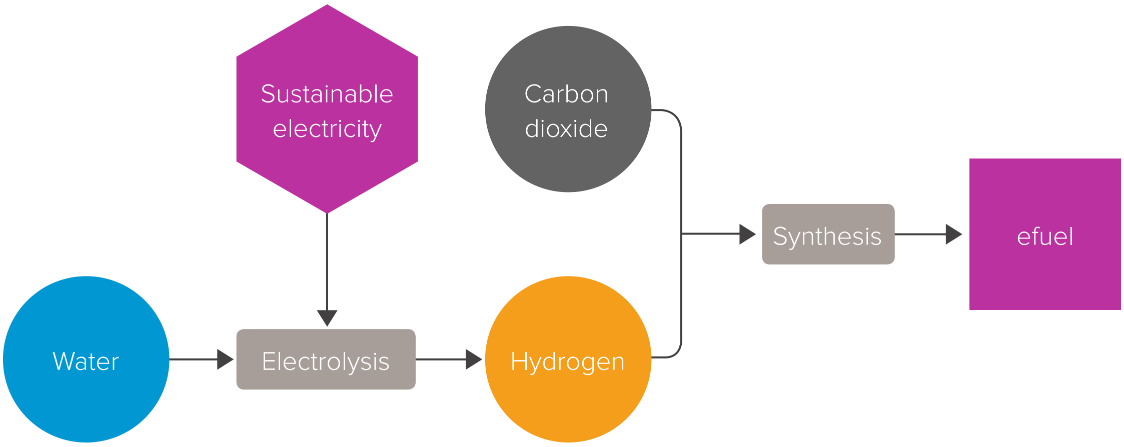
Advantages include high energy density, use of existing infrastructure and compatability with existing engines.

Synthetic electrofuels or efuels are gaseous and liquid fuels produced from hydrogen and captured carbon dioxide using sustainable electricity as the principal power source[23,24]. They are also known as power-to-gas/liquids/fuels (PtX) or synthetic fuels[25]. Figure 5 gives a schematic showing the production of efuels.

The principal advantages of efuels are that they have a relatively high energy density, they use the existing energy infrastructure and are compatible with existing internal combustion engines, albeit with slight modifications.

FIGURE 5

Production of efuels[26].



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23. Grahn M, Brynolf S, Taljegård M, Hansson J. 2016 Electrofuels: a review of pathways and production costs. See http://publications.lib.chalmers.se/records/fulltext/245461/local_245461.pdf (accessed 17 April 2019).
24. German Energy Agency. 2017 The potential of electricity-based fuels for based fuels for low-emission transport emission transport in the EU. See https://www.vda.de/en/services/Publications/%C2%ABe-fuels%C2%BB-study---the-potential-of-electricity-based-fuels-for-low-emission-transport-in-the-eu.html (accessed 17 April 2019).
25. Brynolf S, Taljegård M, Grahn M, Hansson J. 2018 Electrofuels for the transport sector: A review of production costs. Renewable and Sustainable Energy Reviews, 81, 1887-1905. (doi: 10.1016/j.rser.2017.05.288).
26. *Op. cit.*, note 24

1.1 Efuel production

There are many different efuels, all produced using the following key process steps:

i. **The production of hydrogen**
The most common industrial process to generate hydrogen is steam methane reforming which uses natural gas and produces carbon dioxide as a by-product. There are several methods of producing low-carbon hydrogen and they are discussed in the Royal Society policy briefing document *Producing low-carbon hydrogen at scale*[27]. Low-carbon hydrogen can be produced by the electrolysis of water using renewable electricity (Figure 5). This will become more commercially viable compared to steam methane reforming with CCS, as the price of sustainable electricity falls and electrolysers become more efficient. The source of the sustainable electricity will also affect the cost, as intermittent sources (eg wind turbines) will increase the cost of electrolysers due to the more challenging intermittent duty cycle.

ii. **The capture of carbon dioxide**
High concentration carbon dioxide sources, such as from industrial processes (eg steel works) or power generation[28], provide a cheaper source of carbon, however it can also be obtained from the air through direct air capture (DAC). DAC technologies are considered in the Royal Society and Royal Academy of Engineering report on Greenhouse Gas Removal[29]. Technologies currently being tested include supported amine absorption and the lime-soda process.

iii. **Synthesis – reacting carbon dioxide with hydrogen to form fuels and chemicals**
Common processes for fuel synthesis include Fischer Tropsch and methanol synthesis (see Box 2). Very large scale plants using these processes are in operation and produce, for example, methane and methanol from carbon monoxide and hydrogen. With research, these processes can be modified to use carbon dioxide as the carbon source, requiring modifications to maintain conversion efficiencies and yields. There are already a number of demonstration processes either on-line or in preparation (see Case Studies 1 and 2 and Annex B).

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[27] *Op. cit.*, note 4

[28] Grahn M, Taljegård M, Ehnberg J, Karlsson S. 2014 Utilising excess power: the case of electrofuels for transport. Systems Perspectives on Renewable Power, ISBN: 978-97-980974-0-5.

[29] The Royal Society and Royal Academy of Engineering. 2018 Greenhouse Gas Removal. See https://royalsociety.org/-/media/policy/projects/greenhouse-gas-removal/royal-society-greenhouse-gas-removal-report-2018.pdf (accessed 17 April 2019).

Image
Vulcanol production plant in Iceland.

CASE STUDY 1

Vulcanol, Carbon Recycling International[30]

Carbon Recycling International (CRI) operates a power-to-methanol production plant that produces commercial scale renewable methanol, called Vulcanol, at 4000 tonnes/year. The plant recycles 5500 tonnes of carbon dioxide/year captured from flue gas of a geothermal power plant located next to the CRI plant. The carbon dioxide is combined with hydrogen produced by electrolysis of water powered by renewable energy (hydro, geothermal and wind sources).

Vulcanol can either be used directly in vehicles compatible with 100% methanol; blended with petrol to be used in the production of biodiesel or fuel ethers such as DME, OME etc.; or could be used, for example, as a low-carbon feedstock for the production of chemicals.

In 2017, CRI established a project pipeline in China (CRI Ji Xin) as a joint venture with a Shanghai company to develop a methanol plant design with a nominal 50,000 tonnes/year production capacity.

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30. Carbon Recycling International. Vulcanol. See http://www.carbonrecycling.is/vulcanol (accessed 18 April 2019).

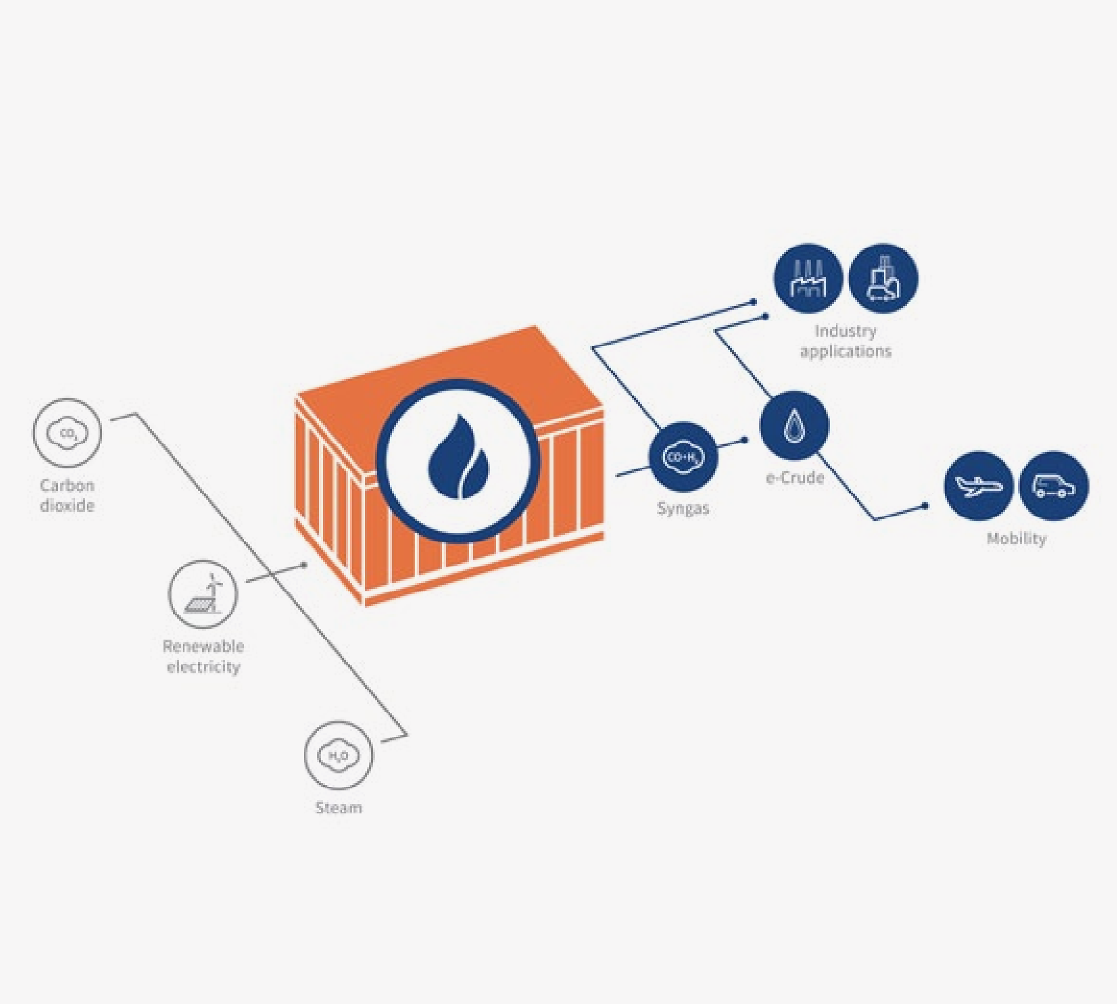

Image
Production of e-crude.
© ®Sunfire GmbH.

CASE STUDY 2

Sunfire e-crude[31]

A 20 MW facility is to be installed by Sunfire in Herøya, Norway, which will produce 8000 tonnes of 'e-crude' liquid fuel/year from renewable energy and carbon dioxide with a target price of below €2/litre. The plant will be built in 2022 and operated by Norsk e-Fuel.

Carbon dioxide is partly extracted on-site through Direct Air Capture (DAC) technology. From carbon dioxide and water, syngas is produced through electrolysis using renewable electricity. Via Fischer Tropsch, the syngas is converted to 'e-crude', a renewable crude oil substitute.

'E-crude' can be refined to generate e-diesel or e-jet fuel; this is currently being investigated by several leading manufacturers.

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[31] Sunfire, 2017 First commercial plant for the production of blue crude planned in Norway. See https://www.sunfire.de/en/company/news/detail/first-commercial-plant-for-the-production-of-blue-crude-planned-in-norway (accessed 17 April 2019).

Smaller scale Fischer Tropsch plants would be needed to take advantage of isolated renewable electricity or carbon sources.

1.2 Future developments

1.2.1 Scaling down Fischer Tropsch

Commercial Fischer Tropsch plants are normally built on a large scale. Smaller scale Fischer Tropsch plants would be needed to take advantage of isolated renewable electricity or carbon sources. These are being developed, for example, CompactGTL have a fully commercialised modular plant in Kazakhstan that produces 2500 barrels/day of synthetic crude[32].

1.2.2 Electrolysis

Producing low-carbon hydrogen through the electrolysis of water will become more commercially viable as the price of renewable electricity falls and the electrolysers become more efficient. Research is underway to improve the costs of electrolysis and is already starting to yield benefits. For example, Thyssenkrupp claim their advanced electrolyser technology can make large scale hydrogen production from renewable electricity economically attractive by achieving high efficiencies of around $69\%_{LHV}$[33].

There is interest in the direct conversion of carbon dioxide to fuels using electricity with special electrocatalyst electrodes to, for example, by reducing carbon dioxide to carbon monoxide and then converting it to a fuel or reducing it directly to methanol or methyl formate[34 – 36].

1.2.3 Bacterial conversion

Bacterial conversion of carbon dioxide to efuels without directly using biomass, is also an area of current research. Electrochaea GmbH has developed a biocatalyst to combine low-carbon hydrogen and atmospheric carbon dioxide in a bioreactor to produce synthetic methane[37].

1.2.4 Solar to fuels

Solar or photocatalytic conversion of carbon dioxide has been actively studied for a number of years[38 – 40]. It involves the activation of catalysts using light to convert carbon dioxide directly into fuels such as methanol. Catalysts based on titanium dioxide are most commonly used because of their high efficacy. Despite progress, there have been a number of challenges limiting its widespread uptake and in particular, more work needs to be done on conversion rates, overall yields and selectivity. Recent work focussing on modified graphene has reported useful rates of production for methane and ethane from carbon dioxide with sunlight[41]. While these levels are still ultimately very low, this work suggests that with further development higher rates could be achievable.

Research is also continuing into the direct solar conversion of water vapour into hydrogen with efficiencies of up to 15% being reported[42].

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32. CompactGTL. Projects. See http://www.compactgtl.com/about/projects/ (accessed 17 April 2019).
33. Thyssenkrupp. 2018 Hydrogen from large-scale electrolysis. See https://www.thyssenkrupp-uhde-chlorine-engineers.com/en/products/water-electrolysis-hydrogen-production/ (accessed 17 April 2019).
34. Al-Omari AA, Yamani ZH, Nguyen HL 2018 Electrocatalytic CO2 reduction: From homogeneous catalysts to heterogeneous-based reticular chemistry. Molecules, 23, 2835. (doi:10.3390/molecules23112835).
35. De Luna P *et al*. 2018 Catalyst electro-redeposition controls morphology and oxidation state for selective carbon dioxide reduction. Nature Catalysis, 1, 103-110. (doi:10.1038/s41929-017-0018-9).
36. Feng DM, Zhu YP, Chen P, Ma TY. 2017 Recent Advances in Transition-Metal-Mediated Electrocatalytic CO2 Reduction: From Homogeneous to Heterogeneous Systems. Catalysts, 7, 371. (doi:10.3390/catal7120373).
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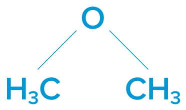
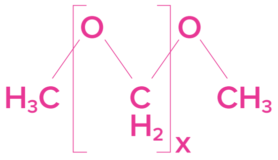
38. Piumetti M, Fino D, Russo N. 2014 Photocatalytic Reduction of CO2 into Fuels: A Short Review. Journal of Advanced Catalysis Science and Technology, 1, 16-25. (doi: 10.15379/2408-9834.2014.01.02.03).
39. Tuller HL. 2017 Solar to fuels conversion technologies: a perspective. Materials for Renewable and Sustainable Energy, 6, 3. (doi: 10.1007/s40243-017-0088-2).
40. Marxer DA *et al*. 2015 Demonstration of the entire production chain to renewable kerosene via solar-thermochemical splitting of H2O and CO. Energy Fuels, 29, 3241-3250. (doi:10.1021/acs.energyfuels.5b00351).
41. Sorcar S *et al*. 2018 High-rate solar-light photoconversion of CO2 to fuel: controllable transformation from C1 to C2 products. Energy and Environmental Science, 11, 3183-3193. (doi: 10.1039/C8EE00983J).
42. Heremans G *et al*. 2017 Vapor-fed solar hydrogen production exceeding 15% efficiency using earth abundant catalysts and anion exchange membrane. Sustainable Energy and Fuels. 1, 2061–2065. (doi:10.1039/c7se00373k).

1.2.5 New efuels

The development of new efuels raises the potential to improve existing internal combustion engines in relation to efficiency, greenhouse gas contribution and emissions. New oxygenated efuels are being developed for use in existing diesel engines, and molecules such as dimethyl ether (DME) and oxymethylene ethers (OME_x) have been developed and deployed in heavy-duty vehicles by companies such as Ford and Volvo Trucks. Reduced carbon dioxide emissions from DME/OME_x are claimed[43,44], but the extent is yet to be proven as much of the data is from idealised test scenarios.



DME



OME_x

$x = 0 = OME_0 = DME$
$x = 1 = OME_1$
$x = 2 = OME_2$ etc

DME and the lower OMEs are gaseous under ambient conditions and need to be stored under pressure in tanks for distribution and use in the vehicle. Work is ongoing to create longer chain OMEs which are liquids under ambient conditions and easier to store and use.

A Life cycle assessment (LCA) study has shown that a 22% OME/fossil fuel diesel blend by volume could reduce the global warming impact of diesel by 11%[45]. The OME would be produced using hydrogen from electrolysis via intermittent wind energy and carbon dioxide derived from biogas. Further benefits may also be derived from simultaneous fuel/combustion system optimisation and new efuel formulations that reduce engine pollutant emissions.

Ethanol is well established as a fuel or fuel blend in some countries and other alcohols are becoming popular. These include methanol produced from carbon dioxide (see Case Study 1) which has found increasing use in marine engines (eg Stena Line[46]), where fuel tolerance is less of an issue than in road vehicle engines. Butanol is also an interesting petrol alternative as it has a low vapour pressure, is non-corrosive[47] and has an energy density between ethanol and petrol.

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[43] Deutz S *et al*. 2018 Cleaner production of cleaner fuels: wind-to-wheel – environmental assessment of CO2-based oxymethylene ether as a drop-in fuel. Energy and Environmental Science. 11, 331-343. (doi: 10.1039/c7ee01657c).

[44] Ford. 2015 Press Release: Ford leads project to develop near zero particulate emission diesel cars that could run on converted CO2. See https://media.ford.com/content/fordmedia/feu/en/news/2015/09/11/ford-leads-project-to-develop-near-zero-particulate-emission-die.html (accessed 18 April 18, 2019).

[45] *Op. cit.*, note 43

[46] Stena Line. 2015 Stena Germanica's Methanol Conversion. See https://www.stenalinefreight.com/news/Methanol-project (accessed 30 April 2019).

[47] Dowson GRM *et al*. 2015 Kinetic and economic analysis of reactive capture of dilute carbon dioxide with Grignard reagents. Faraday Discussions, 183, 47-65. (doi: 10.1039/c5fd00049a).

BOX 3

UK research expertise

UK expertise in efuels is strong with a number of research centres developing new technologies to improve and scale up the use of renewable energy to electrolyse water and to improve the direct conversion of carbon dioxide. This has been promoted by the UK government through a number of funding calls such as the *Future fuels for flight and freight* which although not specifically focused on efuels has led to innovation in this area[48]. There are a number of EPSRC funded research groups working on the direct conversion of carbon dioxide by the electrocatalytic reduction of or via syngas[49 – 53].

Other UK research groups are focused on electrolyser technology for the production of hydrogen using renewable electricity, which can then be used to reduce carbon dioxide. Examples include research into electrolysers, which has led to the commercialisation of PEM electrolysers[54] and other efuel applications such as synthetic methane via biomethanation[55].

Catalysis expertise in the UK is strong and typically spans science and engineering faculties across the UK HEI with close industrial interaction. The UK historically has a very strong track record of innovation and implementation of catalysts for petrochemical conversions which underpins the chemical industry. The UK Catalysis Hub is located at Harwell and involves collaborations with more than 40 UK HEIs and a wide range of businesses[56].

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48. Department of Transport. 2018 Government funding boost for low-carbon fuels development. See https://www.gov.uk/government/news/government-funding-boost-for-low-carbon-fuels-development (accessed 10 May 2019).
49. UK Research and Innovation: EPSRC. 2018 Electroreduction of carbon reduction to sustainable fuels. Imperial College London. See https://gtr.ukri.org/projects?ref=studentship-2132098 (accessed 18 April 2019).
50. UK Research and Innovation: EPSRC. 2013 Nano-structured catalysts for CO2 reduction to fuels. Imperial College London. See https://gow.epsrc.ukri.org/NGBOViewGrant.aspx?GrantRef=EP/H046380/1 (accessed 18 April 2019).
51. UK Research and Innovation: EPSRC. 2016 Liquid fuel and bioEnergy supply from CO2 reduction. Newcastle University. See https://gow.epsrc.ukri.org/NGBOViewGrant.aspx?GrantRef=EP/N009746/1 (accessed 15 May 2019).
52. UK Research and Innovation: EPSRC. 2016 Flexible routes to liquid fuels from CO2 by advanced catalysis and engineering. University of Liverpool. See https://gow.epsrc.ukri.org/NGBOViewGrant.aspx?GrantRef=EP/N010531/1 (accessed 15 May 2019).
53. UK Research and Innovation: EPSRC. 2017 Production of synthetic diesel via CO2 electrolysis. University of St Andrews. See https://gtr.ukri.org/projects?ref=studentship-1949695 (accessed 15 May 2019).
54. UK Research and Innovation: EPSRC. 2014 Temperature and alkali stable polymer electrolytes for hydrogen and carbon dioxide alkaline electrolysers. See https://gow.epsrc.ukri.org/NGBOViewGrant.aspx?GrantRef=EP/M005895/1 (accessed 15 May 2019).
55. UK Research and Innovation: Gateway to Research. 2015 Synthetic Methane: Enabling renewable energy storage by integrating the electricity and gas networks. ITM Power (Research Limited). See https://gtr.ukri.org/projects?ref=132006 (accessed 18 April 2019).
56. UK Catalysis Hub. See https://ukcatalysishub.co.uk/ (accessed 26 April 2019).

1.3 Research challenges

The main research challenges for efuels are:

a. Improving the fundamental understanding of catalysis

b. Developing more efficient and lower cost electrolysis technologies for the conversion of water to low-carbon hydrogen

c. Engineering and catalytic developments to make small scale conversion of syngas or other electro-derived intermediate chemicals into chemicals and fuels more commercially attractive and scale better to renewable generators eg wind farms

d. Adapting to the intermittency of renewable electricity

e. Developing processes that can be scaled up to the gigawatt output size

f. Matching fuels to engine requirements, for example tailor made efuels from methanol to optimise engine performance

1.4 Technology Readiness Levels (TRLs)

There are a wide range of efuel technologies and many are already commercial, for example those developed by Carbon Recycling International to produce methanol from carbon dioxide, hydrogen, and renewable electricity (see Case Study 1). Technologies at small to medium scale include gas-to-liquids technologies.

Technologies at the lower levels of development include electrolytic carbon dioxide conversion (perhaps TRL 4 – 6) and synthetic natural gas (TRL 5 – 8), and at very early stage research are activities such as electrophotocatalytic conversion. There is significant work going on looking at the fundamental science of efuels at TRL 1 – 3 levels in UK universities.

1.5 Timelines

In the medium term (5 – 10 years), efuel processes will most likely be incorporated into existing fuel manufacturing processes to improve carbon efficiency and initially, make use of any excess renewable energy. This gradual introduction into the marketplace will be driven by the availability of renewable energy. In the longer term (10+ years), processes with highly innovative fuels are likely to appear in the marketplace; such as the new DME and OME_x fuels as drop-ins for internal combustion engines.

Synthetic biofuels

Including biofuels in the energy mix reduces cumulative carbon emissions and the cost of meeting 2050 carbon objectives.

Synthetic biofuels are produced from hydrocarbons from biological sources using chemical and thermal methods. A range of processes are used to convert biomass feedstock into different synthetic biofuels, as shown in Figure 6.

This report does not directly address the biological production of biofuels, but looks at the chemical processing of biomass and the further chemical processing of biologically produced fuels. For more information on the production of biofuels, see the *Sustainability of liquid biofuels* report by the Royal Academy of Engineering[57].

Including biofuels in the energy mix reduces cumulative carbon emissions and the cost of meeting 2050 carbon objectives[58,59]. The largest carbon savings are obtained from using second-generation feedstocks such as agricultural residues, wood wastes and other waste materials. The supply of sustainable biofuels will be limited by the availability of such feedstocks, particularly as food production may take precedent over energy in the UK and around the world.

2.1 Future of synthetic biofuels

In 2017/18 1,621 million litres of biofuel were supplied in the UK (81% met sustainability requirements) and were composed mainly of bioethanol, biodiesel and biomethanol. The Renewable Transport Fuel Obligation (RTFO) have amended the biofuels volume blend target from 4.75% to 12.4% in 2032[60]. Policy changes like this have generated market incentives and investor confidence in UK biofuel production. Forecasts for 2032 indicate that sustainably sourced bioenergy could contribute to between 15 – 25% of the UK's primary energy demand[61,62]. This would require substantial use of wastes and residues, such as straw and slurry, and would have significant associated cost and infrastructure implications[63].

The decision of how best to use this limited resource, will depend upon a number of factors. These include the life cycle analysis of the options, the type/location of biomass available, the carbon capture and storage capacity available (if considering bioenergy with carbon capture and storage (BECCS)) and the political and environmental priorities[64]. These constraints suggest that synthetic biofuel production might be best employed either by combining with batteries in a hybrid vehicle, or by prioritising the use of synthetic biofuels in a difficult transport mode eg aviation, offering a lower risk and cost route to low-carbon transport[65].

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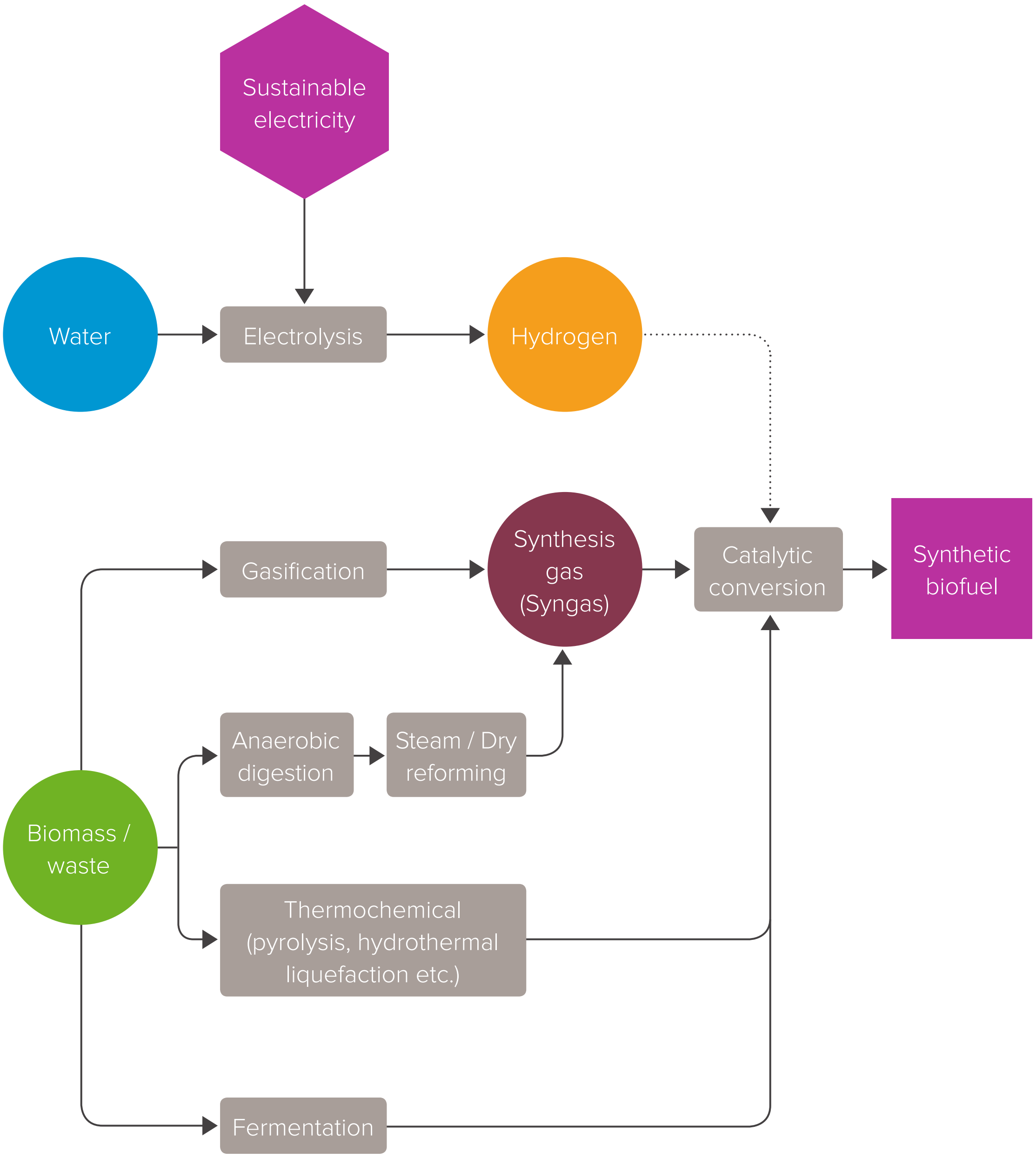
57. Royal Academy of Engineering. Sustainability of liquid biofuels. See https://www.raeng.org.uk/publications/reports/biofuels (accessed 30 April 2019)
58. Energy Technologies Institute. 2018 The role for bioenergy in decarbonising the UK energy system. See https://d2umxnkyjne36n.cloudfront.net/insightReports/FINAL-The-role-for-Bioenergy-in-decarbonising-the-UK-energy-system.pdf?mtime=20181029175142 (accessed 17 April 2019).
59. Committee on Climate Change. 2018 Biomass in a low-carbon economy. See https://www.theccc.org.uk/wp-content/uploads/2018/11/Biomass-in-a-low-carbon-economy-CCC-2018.pdf (accessed 17 April 2019).
60. Department for Transport. RTFP Guidance Part One Process Guidance 2019. See https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/803811/rtfo-guidance-part-1-process-guidance-year-2019.pdf (accessed 17 April 2019).
61. Renewable Energy Association. 2019 Bioenergy Strategy Phase 2: A Vision to 2032 and Beyond. See https://www.bioenergy-strategy.com/publications (accessed 17 April 2019).
62. Welfle A, Gilbert P, Thornley P. 2014 Securing a bioenergy future without imports. Energy Policy, 68, 1-14. (doi: 10.1016/j.enpol.2013.11.079).
63. *Op. cit.*, note 58
64. Thornley P, Gilbert P, Shackley S, Hammond J. 2015 Maximizing the greenhouse gas reductions from biomass: the role of life-cycle assessment. Biomass and Bioenergy, 81, 35-43. (doi: 10.1016/j.biombioe.2015.05.002).
65. Chuck, CJ. 2016 Biofuels for Aviation: Feedstocks, Technology and Implementation. Academic Press. (doi: 10.1016/C2014-0-03505-8).

FIGURE 6

Schematic of common production routes for synthetic biofuels.



A number of demonstration synthetic biofuel facilities have been set up, for example, Greenergy in Teesside (Case study 3), and Fulcrum BioEnergy in Nevada, who have developed a municipal waste-to-liquids process that produces a liquids stream from municipal waste via the Fischer Tropsch process[67].

Image
Greenergy biodiesel plant, Teesside.

CASE STUDY 3

Greenergy International Ltd, Teesside

Greenergy is a UK supplier of road fuel and produces 75% of biofuels used in the UK. Their biodiesel is produced from global waste feedstocks such as used cooking oil and food waste. They run three manufacturing facilities in Teesside, Immingham and Amsterdam (planned late-2019). The Teesside biodiesel plant currently receives 4,500 tonnes of used cooking oil per week which is sourced globally from restaurants, fast food outlets and food producers; to produce 284 million litres of biodiesel per year.

Their B20 diesel contains a biodiesel-from-waste average content of 20% across the year and requires no engine modifications. In 2016, Transport for London and Low-carbon Vehicle Partnership (LowCVP) commissioned a project to fuel one third of the TfL bus network with B20 biodiesel[66].

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[66] Supergen Bioenergy Hub. See http://www.supergen-bioenergy.net/ (accessed 25 June 2019).

[67] Johnson Matthey and BP. 2018 Press Release: BP and Johnson Matthey license innovative waste-to-fuels technology to biofuels producer Fulcrum BioEnergy. See https://matthey.com/-/media/files/articles/bp-and-jm-license-technology-to-fulcrum-final-aqdocx.pdf (accessed 17 April 2019).

2.2 Research challenges

The majority of research challenges for synthetic biofuels centre on:

- Exploring options for the production of sustainable biomass feedstocks
- Developing new pre-treatment and conversion technologies for the wide range of feedstock parameters encountered with typical feedstocks
- Integrating available conversion techniques to develop efficient processes that deliver a desirable combination of fuels and bio-products
- Adapting existing conversion systems for new fuel properties
- Identifying desirable process combinations that maximise the benefits of affordability, resilience and carbon reductions and deliver wider ecosystem benefits

BOX 4

UK research expertise

The focal point for UK biofuel research is the Supergen Bioenergy Hub at Aston University[68]. This is a research consortium jointly funded by EPSRC and BBSRC, bringing together academia, industry and societal stakeholders to develop sustainable bioenergy systems. The hub mainly operates at TRLs 1 – 3, though it also carries out significant systems analysis/synthesis research.

There are also a number of BBSRC funded networks in industrial biotechnology, which operate at slightly higher TRLs and particularly focus on bringing together industrialists and academic partners to develop joint projects and activities. These include the Biomass Biorefinery Network (BBNet), led by the University of York[69].

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[68] UK Research and Innovation. Biomass Biorefinery Network (BBNet). See https://gtr.ukri.org/projects?ref=BB%2FS009779%2F1 (accessed 25 June 2019).

[69] Transport for London. 2015 One third of London's buses to run on waste fats and oils. See https://tfl.gov.uk/info-for/media/press-releases/2015/december/one-third-of-london-s-buses-to-run-on-waste-fats-and-oi (accessed 13 May 2019).

2.3 Technology Readiness Levels (TRLs)

Synthetic biofuel production routes encompass a wide range of conversion technologies at different TRLs[70]. Fully commercialised routes in operation today include crop oils or waste cooking fats to biodiesel. Little innovation is needed in the processing to switch to alternative oils to feed the process.

Fuels based on agricultural residues, waste food and sustainable wood (lignocellulosic) have been demonstrated to TRL 8, however full industrial production is hampered by high costs. Further from market, with innovation still required for full exploitation, are pyrolysis based fuels (TRL 7), alcohol to jet fuels (TRL 6) and hydrothermal liquefaction of wet municipal wastes and sewage (TRL 5 – 6). Direct hydrocarbon and chemical upgrading production from sugar has also been demonstrated (TRL 6), but has not been taken further than pilot scale. Alternative next generation feedstocks for these processes, including microalgae, yeast based oils and macroalgae (seaweed), remain at TRL 3 – 4[71].

The scientific understanding of the whole systems analysis is well developed in most areas for lignocellulosic fuels. However, basic research at TRLs 1 – 3 is required to confirm the sustainability of particular biofuel systems especially when integrated with alternative product formation.

2.4 Timelines

The majority of conversion technologies are constrained by relatively high costs derived from limited economies of scale and the availability and price of feedstock[72]. As such, a 3 – 5 year timeframe for the pyrolysis of lignocellulosic feedstocks is feasible to achieve market penetration, but only given a suitable economic climate[73]. Similarly, the conversion of wet municipal wastes and food waste through hydrothermal liquefaction has been demonstrated at pilot scale across the world, it is likely this will start to achieve market penetration within 5 years[74,75].

In the medium term (5 – 10 years) it is likely that alcohol to jet, Fischer Tropsch fuels and other combined biological/chemical processes will start to appear, especially for the aviation sector. It is unrealistic to expect microalgal-derived fuel production in the UK due to the climate, although in the longer term (10+ years) macroalgal-derived fuels could become part of the UK energy mix.

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70. Bacovsky D, Ludwiczek N, Ognissanto M, Wörgetter M. 2013 Status of advanced biofuels demonstration facilities in 2012. See http://task39.sites.olt.ubc.ca/files/2013/12/2013_Bacovsky_Status-of-Advanced-Biofuels-Demonstration-Facilities-in-2012.pdf (accessed 15 May 2019).
71. Laurens LML. 2017 State of technology review–algae bioenergy, an IEA bioenergy inter-task strategic project. See http://www.ieabioenergy.com/wp-content/uploads/2017/01/IEA-Bioenergy-Algae-report-update-20170114.pdf (accessed 15 May 2019).
72. Karatzos S, McMillian JD, Saddler JN. 2014 The potential and challenges of drop-in biofuels. See http://task39.sites.olt.ubc.ca/files/2014/01/Task-39-Drop-in-Biofuels-Report-FINAL-2-Oct-2014-ecopy.pdf (accessed 15 May 2019).
73. Biomass Technology Group. Technologies: Fast pyrolysis. See http://www.btgworld.com/en/rtd/technologies/fast-pyrolysis (accessed 25 June 2019).
74. Tews IJ *et al*. 2014 Biomass direct liquefaction options – technoeconomic and life cycle assessment. See https://www.osti.gov/biblio/1184983-biomass-direct-liquefaction-options-technoeconomic-life-cycle-assessment (accessed 18 April 2019).
75. Aarhus University. Department of Engineering Research: HTL Pilot Plant. See https://eng.au.dk/en/research/laboratory-facilities/htl-pilot-plant/ (accessed 25 June 2019).

Challenges and benefits for widespread adoption of synthetic biofuels and efuels

3.1 Costs

3.1.1 Efuel costs

The current cost of efuels is estimated to be around €4.50/litre for diesel equivalent[76] but this depends primarily on the cost of sustainable electricity. No industrial scale plant has yet been built, but several comprehensive studies on the future costs of efuels have been published using forecasts[77 – 79].

There is considerable divergence in these forecasts due to the wide variation in power costs, operation time, electrolyser costs, source of carbon dioxide and the capital interest rates used. For example, renewable power prices vary from about €25/MWh using solar in North Africa to about €50/MWh using wind in Europe in 2050.

Using these forecasts, Figure 7 was developed with a single price set and 6% interest rate to show the cost range of future efuels.

The key drivers for the forecast cost reduction can be seen in Figure 8. Capital cost reduction is almost entirely from electrolysis, as illustrated by the analysis in Figure 9. Note that the operating and maintenance (O&M) costs are dependent on capital cost.

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[76] German Energy Agency. 2017 The potential of electricity-based fuels for based fuels for low-emission transport emission transport in the EU. See https://www.vda.de/en/services/Publications/%C2%ABe-fuels%C2%BB-study---the-potential-of-electricity-based-fuels-for-low-emission-transport-in-the-eu.html (accessed 17 April 2019).

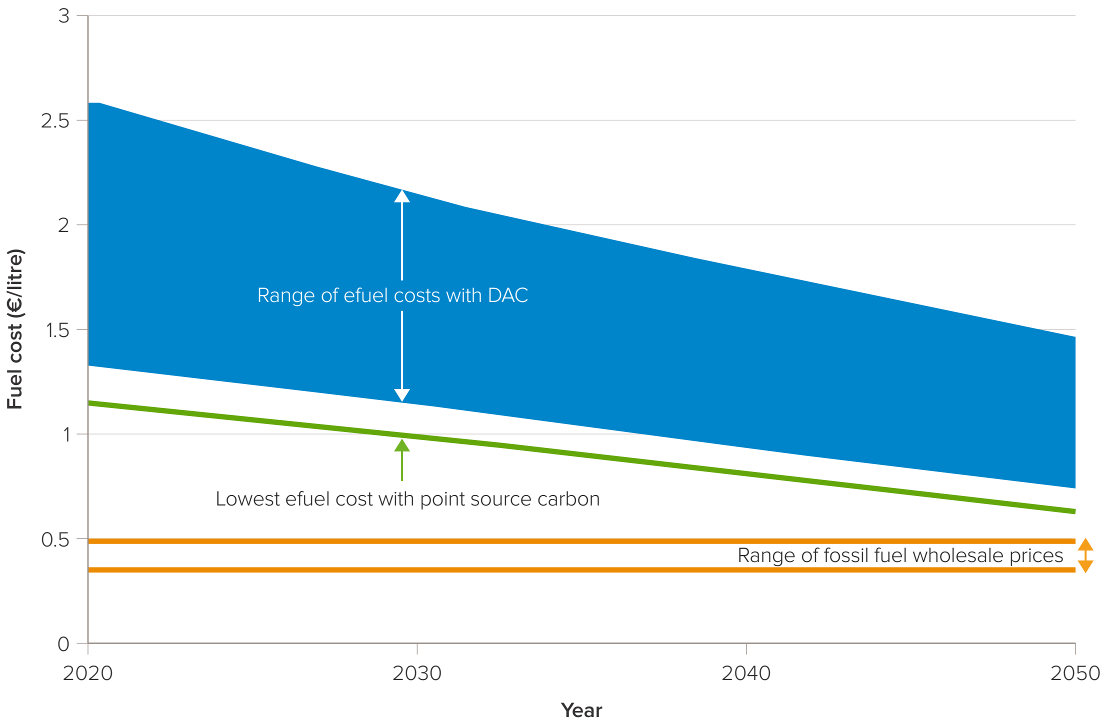
[77] Prognos AG, DBFZ, UMSICHT. 2018 Status of and Perspectives for Liquid Energy Sources in the Energy Transition. See https://www.upei.org/all-news/download/519/421/17?method=view (accessed 18 April 2019).

[78] Agora Verkehrswende, Agora Energiewende, Frontier Economics. 2018 The Future Cost of Electricity-Based Synthetic Fuels. See https://www.agora-energiewende.de/fileadmin2/Projekte/2017/SynKost_2050/Agora_SynKost_Study_EN_WEB.pdf (accessed 18 April 2019).

[79] Schmidt PR, Zittel W, Weindorf W, Raksha T. 2016 Renewables in Transport 2050: Empowering a sustainable mobility future with zero emission fuels from renewable electricity. See http://www.lbst.de/news/2016_docs/FVV_H1086_Renewables-in-Transport-2050-Kraftstoffstudie_II.pdf (accessed 18 April 2019).

FIGURE 7

Efuel cost forecasts.



Note: Based on 3 technology options for diesel using Direct Air Capture[80 – 82], 6% interest rate, 25 years' project lifetime, using solar (2344 hours/year) and wind power (3942 hours/year).

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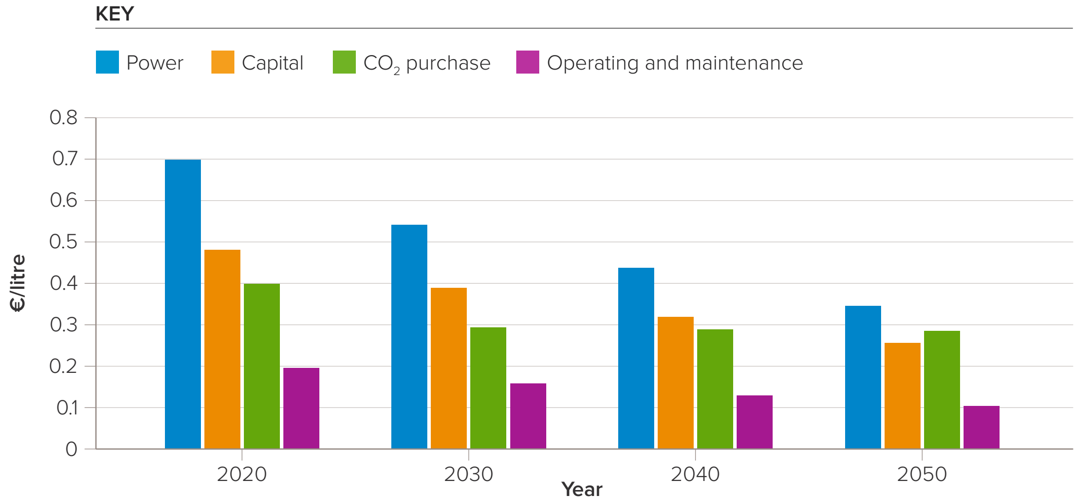
80. *Op. cit.*, note 77
81. *Op. cit.*, note 78
82. *Op. cit.*, note 79

FIGURE 8

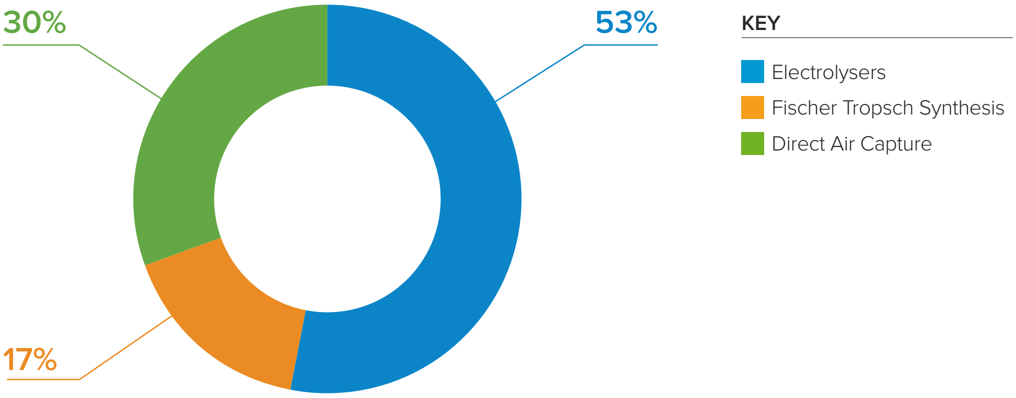
Contributions to the total efuel cost[83].



Note: Based on 6% interest rate, 25 years' project lifetime, replacement of stacks after 15 years, using solar power (2344 hours full load hours/year).

FIGURE 9

Distribution of capital cost of efuels[84].



Note: Based on 6% interest rate, 25 years' project lifetime, Direct Air Capture from Temperature Swing Absorption (TSA), using solar power (capacity factor not included in electrolyser capital estimate).

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[83] *Op. cit.*, note 78

[84] Carbon Engineering. Direct Air Capture. See https://carbonengineering.com/about-dac/ (accessed 18 April 2019).

In addition to electrolyser costs, capital costs also consist of:

- **Carbon capture costs**
  These vary depending on the carbon dioxide concentration and purity of the source. If a pure stream of carbon dioxide is available from an industrial process, for example a fermentation plant, then the capture costs are low, at around €10/tonne. Capturing carbon dioxide directly from the air, where the concentration is very low, is more expensive (example projects include Carbon Engineering[85] and ClimeWorks[86]). The capital costs of these type of facilities at scale are highly uncertain today because only small scale units have been built thus far.
- **Fischer Tropsch synthesis costs**
  Fischer Tropsch conversion technology is well developed at scale. Synthetic fuel plants, especially those based on biomass, tend to be much smaller in scale than current commercial facilities, and therefore cause upward pressure on the capital cost power unit output as economies of scale are lost. Overall, the capital costs for a Fischer Tropsch synthesis unit are in the region of €30 – 40k/barrels of oil equivalent/day[87] and for an equivalent scale efuels Fischer Tropsch synthesis unit, the capital cost is in the region of €200k/barrels of oil equivalent/day, based on electrolyser costs of €1000/kW(electrical).

Absolute capital costs are significant for efuels. For 2050, investment cost forecast estimates range from €200k to €400k/barrels/day[88,89], therefore a 100,000 barrels/day plant would require capital investment of €20 – €40 billion. Jet fuel demand alone in Europe is forecast to be around 1.4 million barrels/day in 2040[90], requiring conversion plant capital of between €280 – 560 billion if all of that demand were to be met by efuels.

The additional sustainable power requirements to make jet efuel for Europe would be between 1,400 and 2,100 TWh/year. For context in 2016, the total electricity generated in the EU was around 3,000 TWh, of which 51% came from sustainable sources[91].

Without further development and scale up, efuels are unlikely to be economically competitive in the 2030 period without government support[92]. However, there are commercial operations targeting a price point much below the current cost, such as the Sunfire efuels plant in Herøya in Norway, which is aiming at €2/litre (see Case Study 2).

Without further development and scale up, efuels are unlikely to be economically competitive in the 2030 period without government support.

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[85] Climeworks. Our products. See https://climeworks.com/our-products/ (accessed 18 April 2019).

[86] *Op. cit.*, note 77

[87] Dimitriou I, Goldingay H, Bridgwater AV. 2018 Techno-economic and uncertainty analysis of Biomass to Liquid (BTL) systems for transport fuel production. Renewable and Sustainable Energy Reviews, 88, 160–175. (doi:10.1016/j.rser.2018.02.023).

[88] *Op. cit.*, note 77

[89] *Op. cit.*, note 78

[90] *Op. cit.*, note 2

[91] Eurostat see https://ec.europa.eu/eurostat/statistics-explained/index.php/Electricity_production,_consumption_and_market_overview#Electricity_generation (accessed 16 May 2019).

[92] International Council on Clean Transportation. 2018 Decarbonization Potential of Electrofuel in the European Union, White Paper. See https://www.theicct.org/sites/default/files/publications/Electrofuels_Decarbonization_EU_20180920.pdf (accessed 17 April 2019).

3.1.2 Biofuel costs

The costs of biofuel production by gasification and pyrolysis has been extensively studied[93 – 101]. Quoted costs are often in the region of €1/litre petrol equivalent, with pyrolysis technologies having the potential for lower production costs than gasification (Figure 10). However, estimated costs are uncertain and this is an area where further work is required to establish the cost basis of this approach.

Synthetic biofuel costs are forecast to be generally lower than efuel costs until at least 2030 though generally exceed fossil fuel prices. There may be scope for synthetic biofuel costs to reduce further over time, but the following uncertainties regarding synthetic biofuels should be noted:

1. While reduced fuel costs can be achieved with low-cost waste feedstocks, the synthetic biofuels produced have characteristics which require further process adaptation with associated costs.
2. Liquid fuels generated by pyrolysis have elevated oxygen levels and unsaturated compounds, which require further processing, in addition to challenging physical properties.

3.2 Life-cycle assessment of synthetic efuels and biofuels

Life cycle assessment (LCA) is an established approach to evaluating and comparing environmental impact over the life cycle of a product or process. It can be used to determine if changing, for example, from a fossil fuel to an efuel was justified on environmental grounds.

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93. Tan ECD *et al*. 2016 Comparative techno-economic analysis and process design for indirect liquefaction pathways to distillate-range fuels via biomass-derived oxygenated intermediates upgrading. Biofuels, Bioproducts and Biorefining, 11, 41–66. (doi: 10.1002/bbb.1710).
94. *Op. cit.*, note 87
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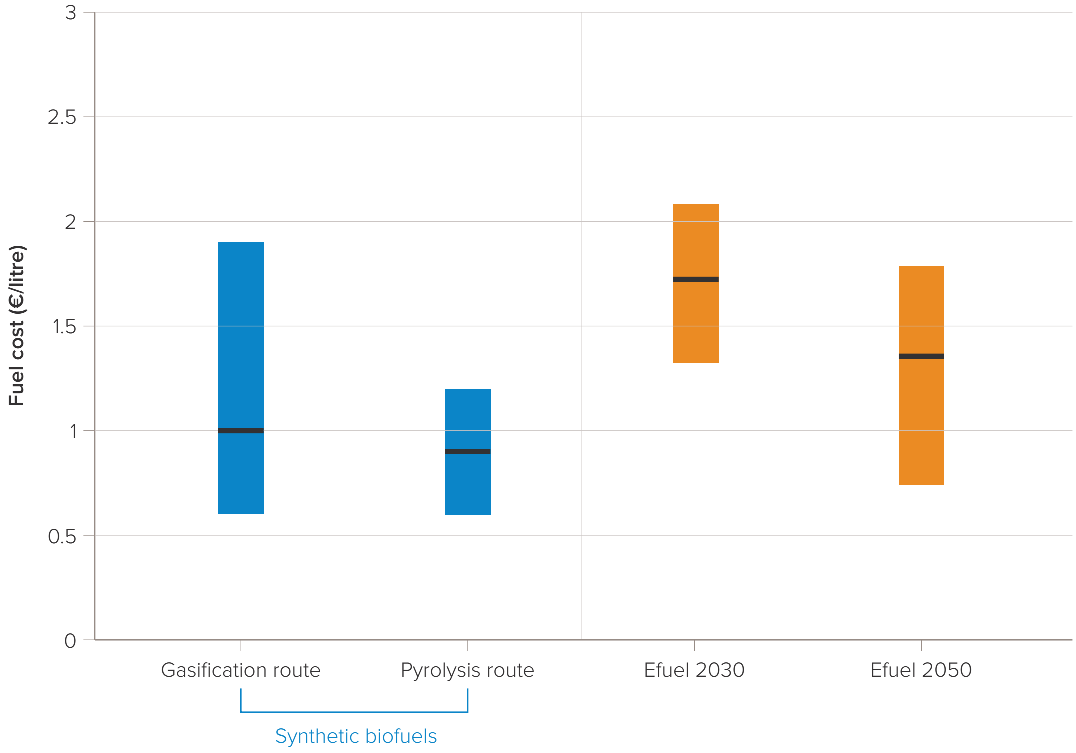
FIGURE 10

Cost of thermochemical conversion of biomass compared with future efuel costs derived from published plant performance and capital data.



Note: Biofuel projections based on 6% interest rate, 20 years' project lifetime and biomass cost of €75/metric tonne. The biofuels costs range is based on first-of-a-kind to nth-of-a-kind plants.

Gasification route includes gasification and conversion. Pyrolysis route includes pyrolysis and hydrogenation.

There are many details in the application of LCA for synthetic efuels and biofuels that must be carefully addressed if the LCA is to provide a consistent and transparent framework. Box 5 demonstrates an approach to LCA for net-zero aviation. Under the European Union's Renewable Energy Directive II (RED II), life cycle approaches can be used to help model mitigation of impact either from long term storage or through avoidance of new fossil carbon entering the supply chain[102].

While research continues to identify methodologies for creating simplified and harmonised guidelines for combined LCA and techno-economic analysis, consistent and transparent LCA of a range of synthetic fuel options are still required.

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BOX 5

Life cycle assessment (LCA) approach for net-zero aviation

Currently, the potential net-zero options for aviation include:

1. Continued use of fossil jet fuel offset with carbon capture and storage (CCS)
2. Replace fossil jet fuel with efuels from captured carbon dioxide

The LCA for option 1 would include the environmental impact of:

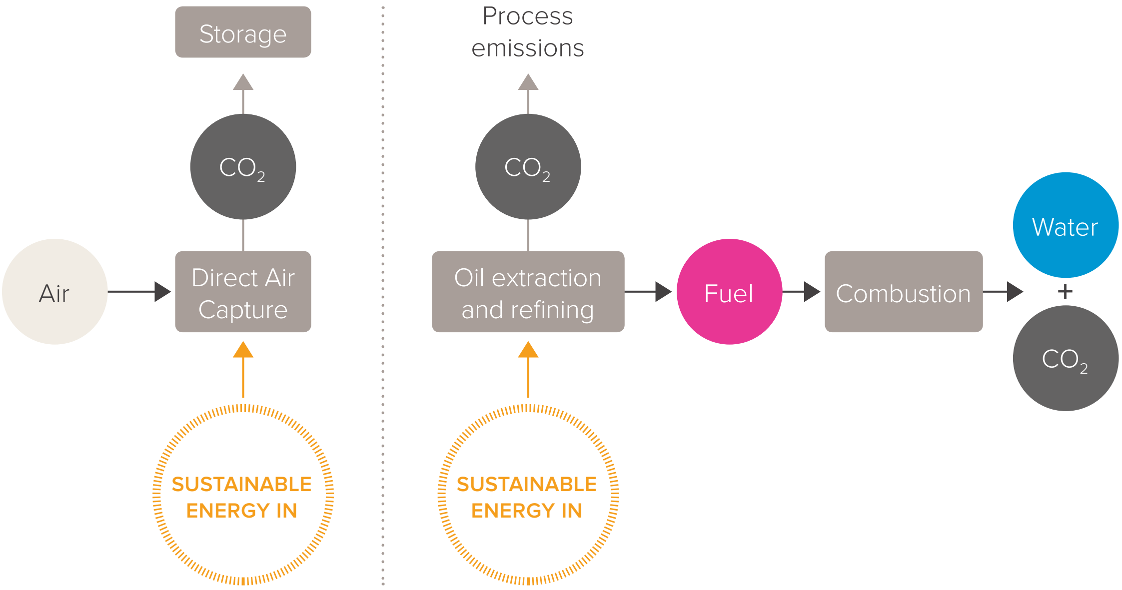
- direct air capture,
- the storage of the carbon dioxide,
- the upstream emissions (extraction of crude oil, processing and delivery) of the jet fuel.

It is important to note that if the overall demand for crude oil products falls in future, the LCA might change if crude oil is extracted only to make jet fuel.

FIGURE 11

Comparison of options for producing and burning jet fuels.

Option 1:
Fossil jet fuel with offsetting



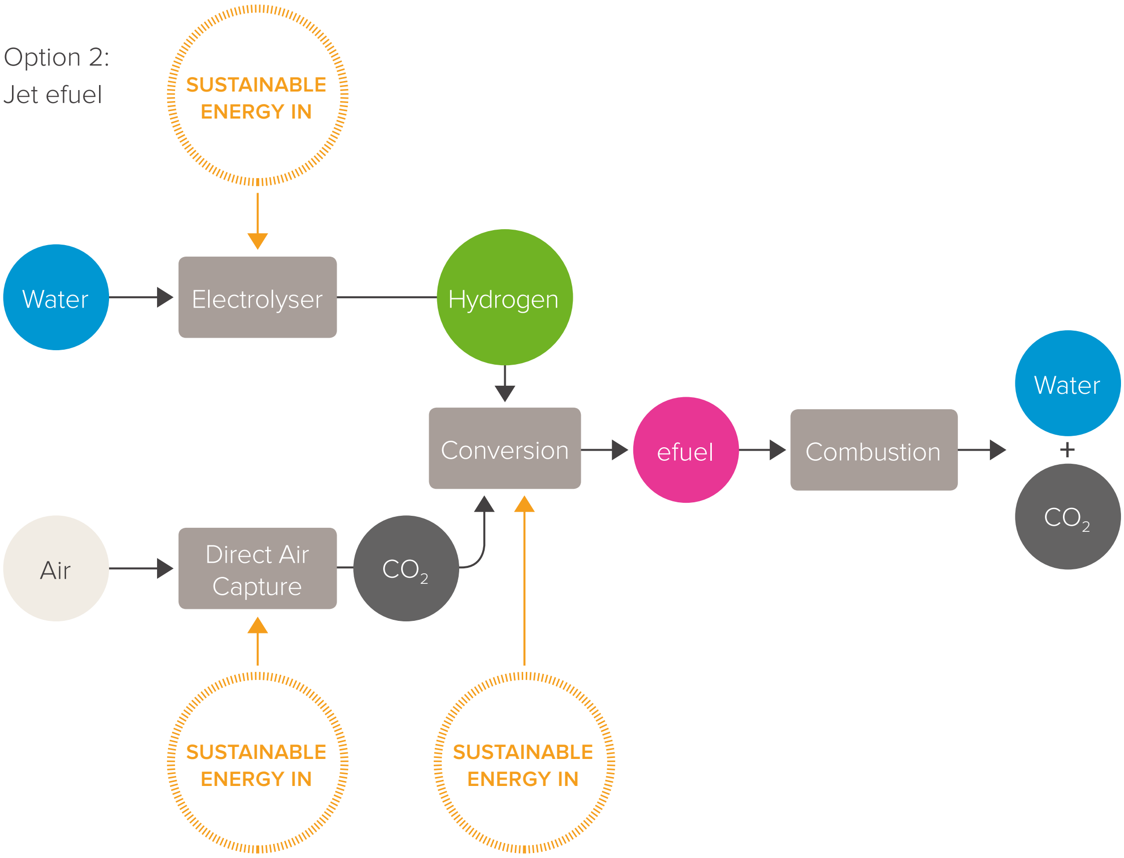
The LCA for option 2 would include the environmental impact of:

- direct air capture,
- the electrolysis of water,
- the fuel conversion process.

It could be assumed that the impact of burning both fossil and synthetic jet fuel would be the same and therefore do not need to be taken into account in the comparison.

However, realistic and transparent LCAs are carried out considering not only carbon dioxide emissions but also the properties of the fuels themselves. Efuels will differ from fossil fuels in their composition, as they have zero sulphur and are linear in molecular shape. This will result in zero sulphur dioxide emissions and also low particulate emissions.

Option 2:
Jet efuel



3.3 Efficiency and input energy needs

Figure 12 shows the comparative overall energy efficiency of powering a vehicle from renewable electricity using an electric motor, a fuel cell and electric motor and an internal combustion engine[103,104]. The losses are due to energy transmission and conversion (eg from electrical energy to chemical energy). It is clear that power-to-efuel diesel offers much lower efficiencies due to energy losses in electrolysis, synthesis and in the internal combustion engine[105].

This inefficiency means that around five times more sustainable electricity would need to be generated to make the efuel diesel to move a vehicle, than is needed to move the same vehicle using an electric motor. This is why battery electric vehicles are likely to become predominant where sufficient electricity can be stored and used. Synthetic efuels and biofuels will be more competitive in transport modes where electricity or other alternatives cannot be used easily, especially if the inefficiencies can be addressed through research and development.

3.4 Potential for production at scale

The many process steps required for the production of both biofuels and efuels are well established at scale within the chemical industry. Similar conversion technologies are used in a number of commercial gas-to-liquid plants to produce low sulphur diesel from natural gas or coal. Examples include Sasol's Secunda coal-to-liquid plant in South Africa, which produces around 160,000 barrels/day (~7.9 million tonnes/year)[106]. Gas-to-liquid plants include Shell's Pearl GTL in Qatar, which produces around 120,000 barrels/day (~5.9 million tonnes/year)[107]. Such plants would require substantial modification to make efuels.

Dimethyl ether (DME) is manufactured at large scale today, both as a fuel product, but also as an intermediate chemical. Oxymethylene ether (OME) manufacture has yet to be widely demonstrated at commercial scale; with only two units greater than 100,000 tonnes/year (~1,200 barrels of oil equivalent/day) having been constructed thus far[108] as the chemistry is complex[109].

The scale up of synthetic biofuels production is limited by the availability of feedstock in sufficient quantity and by gasifier scale up.

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103. *Op. cit.*, note 78

104. Shell Fisita. 2018 Options for Future Fuels – Technical Webinar.

105. *Op. cit.*, note 11

106. Sasol. Secunda Synfuels operations: Overview. See https://www.sasol.com/about-sasol/regional-operating-hubs/southern-africa-operations/secunda-synfuels-operations/overview (accessed 02 May 2019).

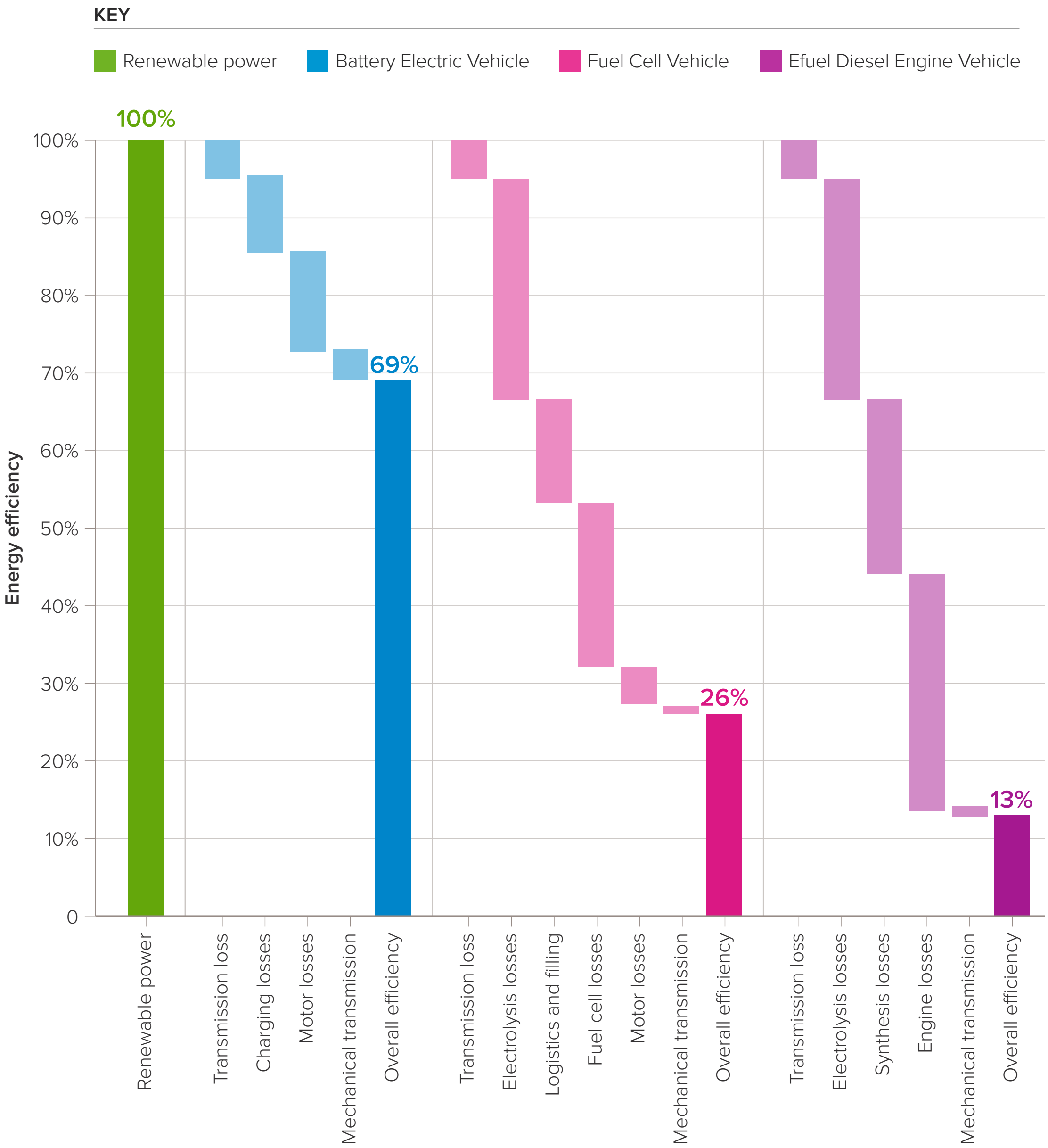
107. Shell Global. Pearl GTL – Overview. See https://www.shell.com/about-us/major-projects/pearl-gtl/pearl-gtl-an-overview.html (accessed 02 May 2019).

108. Hackbarth K, Haltenort P, Arnold U, Sauer J. 2018 Recent Progress in the Production, Application and Evaluation of Oxymethylene Ethers. Chemie Ingenieur Technik, 90, 1520–1528. (doi: 10.1002/cite.201800068).

109. Breitkreuz CF *et al*. 2018 Design of a Production Process for Poly(oxymethylene) Dimethyl Ethers from Dimethyl Ether and Trioxane. Chemie Ingenieur Technik, 90,1489–1496. (doi: 10.1002/cite.201800038).

FIGURE 12

Waterfall chart of pathway efficiencies for low-carbon transport.



The production of efuels at scale is currently limited by the availability of low-cost sustainable electricity to power the generation of hydrogen, the module scale up of the electrolysers and by the generation of syngas. It is likely that centres of production will emerge where such energy sources are abundant (eg wind on the west coast of Africa and solar in desert regions), particularly if direct air capture of carbon dioxide is employed. Efuels are therefore likely to be exported around the world from these centres of production.

Regarding the future global demand of aviation and marine fuels (Table 2), it is clear that there is a potential future market for synthetic liquid fuels, as an initial defossilisation route to decarbonisation. It is estimated that over 100 new production facilities (at current synthetic fuels' commercial scale) worldwide would need to be constructed for liquid synthetic efuels and biofuels to be phased in and fossil energy sources phased out.

TABLE 2

Current estimates for the future worldwide demand for aviation and marine fuels in million tonnes per year[110].

	2030	2035	2040
Aviation	391	406	426
Marine	284	287	286
Total	**675**	**693**	**712**

3.5 Infrastructure requirements for novel synthetic fuels

Oxygenated fuels may be used with varying degrees of infrastructure modification ranging from minimal in the case of ethanol, to significant in the case of DME, which requires pressurised storage. Oxygenated fuels also have lower energy density, thus reducing the utilisation efficiency of the infrastructure on an energy basis.

For comparison, the use of hydrogen in fuel cell vehicles carries significant infrastructure changes and costs, which might include hydrogen pipelines, specialised delivery vehicles and electrolysis units positioned at or near filling stations.

3.6 Additional products

The technology developed to produce liquid synthetic fuels from biomass or from carbon dioxide could also be used to make intermediate molecules for the chemical industry. These molecules are more valuable than fuels and so offer additional incentives for developing the technology.

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[110] *Op. cit.*, note 2

Conclusion

- Synthetic biofuels and efuels offer a medium (5 to 10 years) and a long term (10+ years), transition pathway to decarbonisation by reducing fossil fuel use in transport modes such as shipping, aviation and heavy-duty vehicles.
- A wide range of fuels can be produced, from drop-in replacement fuels to fuels designed to reduce pollution. The chemistry to produce the fuels uses established processes that could be scaled up to meet demand.
- The production of low-cost synthetic efuels at scale will depend upon the availability of low-cost sustainable electricity to produce low-carbon hydrogen amongst other factors such as development of the supply chain. It is likely that efuels will be produced and exported from countries with an abundance of renewable wind, tide or solar energy sources.
- Synthetic biofuels are already produced in volume and widely blended with fossil fuels. Production is limited only by economics and biomass availability. Further research would increase yields and enable a wider range of non-food biogenic materials to be used.
- Synthetic efuels and synthetic biofuels are currently more expensive than conventional fossil fuels. Prices are likely to fall over time as processes are optimised and volumes increased, however policy and regulatory intervention will be needed to ensure earlier adoption and deployment. Early introduction is likely to be as a blend with fossil fuels to reduce the carbon footprint of fossil-based fuels and allow for the development of production at scale.
- Further work needs to be carried out on the of life cycle assessment of biofuels and efuels to ensure that the carbon footprint is smaller than that of fossil fuels. Further research will also need to be carried out to improve process efficiencies, yields and electrolyser capital costs.
- The solutions for decarbonising transport modes will need to be applied internationally to ensure adoption eg for aviation fuel.
- The UK has expertise in many aspects of efuel and biofuel research and development, including in electrolysis and catalysis.
- It is likely that in the next 5 – 10 years, synthetic fuels will be incorporated within existing fossil fuel manufacture to improve carbon efficiency and make use of variable renewable energy production. In the long term (10+ years), it is possible that highly innovative efuels will appear in the marketplace.
- Efuels also offer an option for long term energy storage in the form of liquids for uses other than transport.

Annex A: Definitions

Gasification

Reacting organic material with a controlled amount of oxygen at temperatures greater than 700 °C without combustion. This produces 'synthesis gas', which is primarily a mixture of hydrogen and carbon monoxide with some carbon dioxide.

Carbon dioxide hydrogenation

A reaction of carbon dioxide and hydrogen to form methanol using a metal catalyst

Water Gas Shift

A reversible reaction of carbon monoxide and water to form carbon dioxide and hydrogen

Pyrolysis

The thermal decomposition of biomass occurring in the absence of oxygen. The process produces hydrogen, methane, carbon dioxide and carbon monoxide gases, condensable vapours (tars and oils) and solid charcoal, depending upon the temperature.

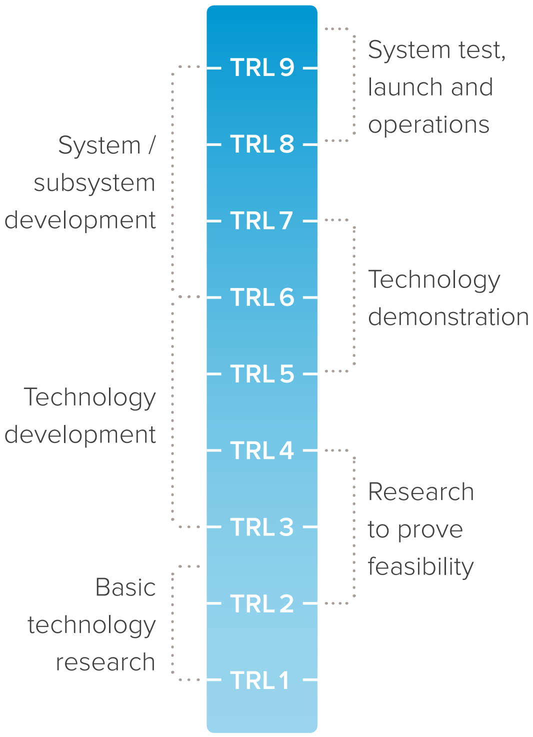
Hydrothermal liquefaction

The thermal depolymerisation of wet biomass (eg sewage sludge) under moderate temperature and high pressure into a crude like mixture of oils.

Lower Heating Value (LHV)

The amount of heat produced from complete combustion of a hydrocarbon not accounting for the heat contained in combustion products if not returned to pre-combustion temperature.

Technology Readiness Levels (TRLs)



Units used in this report

Unit	Description
Barrels	Equivalent to 158.9873 litres
Barrels of oil equivalent	A unit of energy based on the approximate energy released by burning one barrel of crude oil. One BOE as equal to 6.1 GJ, or 1.7 MWh.
TWh	Terawatt-hour, a measure of energy generated or used over a period of time. Equivalent to 1x10^{12} watt-hours

Annex B: Current demonstration efuel plant facilities

(Not exhaustive)

Facility/Operator name	Country	CO_2 feedstock	Efuel output	Output quantity
Carbon Recycling International (Vulcanol)[111]	Iceland	Geothermal plant flue gas	Methanol	4000 tonnes/year
FReSME project (2020)[112]	Sweden	Blast furnace gas	Methanol	50 kg/hr
$MefCO_2$[113] (final phase construction)	Germany	Power plant flue gas	Methanol	1 tonne/day (planned)
Soletair[114]	Finland	Direct Air Capture	Petrol, Kerosene and Diesel	100 kg/hr
Sunfire[115]	Germany	Direct Air Capture	E-Crude (E-diesel)	Demonstration: 3 tonnes in 1500 hrs
Sunfire (2022)[116]	Norway	Direct Air Capture	E-Crude (E-diesel)	8000 tonnes/year (planned 1st stage)

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111. *Op. cit.*, note 30

112. FReSMe. From Residual Steel Gases to Methanol. See http://www.fresme.eu/index.php#PROJECT (accessed 18 April 2019).

113. MefCO2. Methanol fuel from CO2. See http://www.mefco2.eu/ (accessed 18 April 2019).

114. Vázquez FV *et al*. 2018 Power-to-X technology using renewable electricity and carbon dioxide from ambient air: SOLETAIR proof

115. Sunfire. 2017 Sunfire produces sustainable crude oil alternative. See https://www.sunfire.de/en/company/news/detail/sunfire-produces-sustainable-crude-oil-alternative (accessed 18 April 2019).

116. *Op. cit.*, note 31

Annex C: Acknowledgments

This policy briefing is based on discussions from a workshop held at the Royal Society on 8 January 2019 and subsequent input. The Royal Society would like to acknowledge the contributions from those people who attended the workshop and helped draft and review the policy briefing.

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