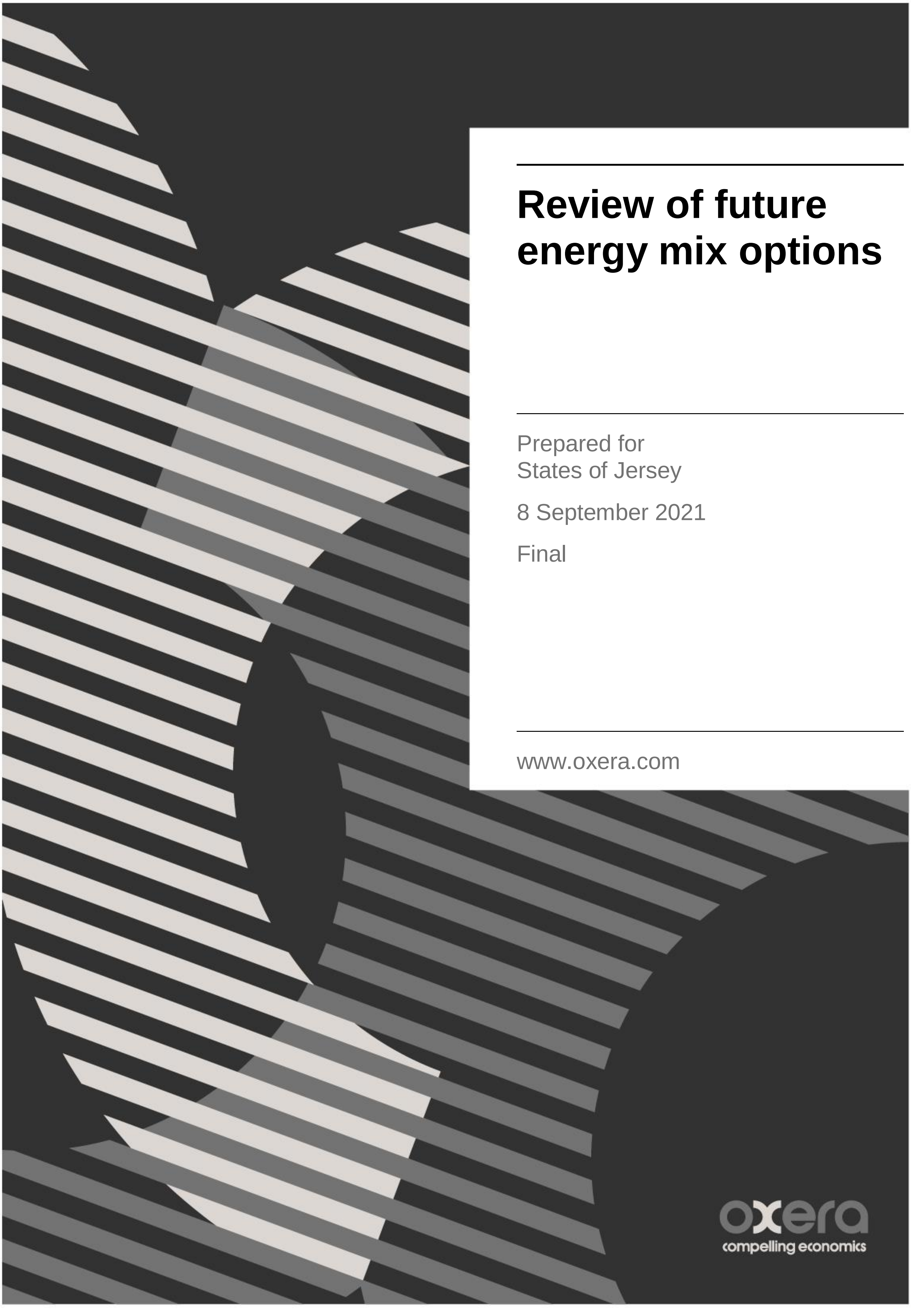

Review of future energy mix options

Prepared for
States of Jersey

8 September 2021

Final

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Contents

Figures and tables

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Executive summary

This report examines the maturity, economic viability and timeframe to viability of technologies that could act as alternatives, or complements, to the use of electricity in Jersey's carbon neutral strategy. In particular, the report evaluates the role of the following technologies in decarbonising transport (marine, air and road) and heating:

- biogas and biomethane;
- liquid biofuels;
- hydrogen.

At this stage, the States of Jersey has asked us to examine the feasibility of biogas, biofuels and hydrogen from a global perspective, rather than for Jersey in particular. Importantly, all three of these energy sources are technologically well established—i.e. the production processes are established and further deployment would be expected to result in significant cost reductions. However, they are not necessarily commercially competitive with fossil fuels, and supply chains have not yet been developed at a large scale. In this report, when we speak of maturity of technology, the focus is therefore on when (and whether) large-scale commercial deployment might be possible.[1] The take-up of biogas, biofuels and hydrogen in Jersey depends on at least the following three factors.

- International acceptance: Jersey is a small market, and it is unlikely to be cost-effective for it to meet all of its energy needs without imported energy. The energy source(s) that are used in its heating and transport will therefore be driven by, and need to be compatible with, technologies that will dominate elsewhere in Europe and internationally.
- Path dependency: the questions of 'which' and 'when' are path-dependent—for example, hydrogen could play a role in the heating networks of various countries by 2050, but only if expenditure on hydrogen production, distribution networks and appliances is undertaken in the preceding decades.
- Policy decisions: governments can play an active role in determining when sustainable alternatives to fossil fuels will become commercially attractive by setting the enabling policies in terms of carbon pricing, taxation and subsidies.

The research undertaken for this report shows that the following conclusions are relevant for Jersey.

1. Low-carbon electricity from French interconnection is a mature and economically viable source for meeting decarbonisation targets in Jersey by 2030. The pathway for delivering cost-effective decarbonisation with alternative technologies is more uncertain, as it requires the technologies to mature to the point of having large-scale commercial deployment potential, and for greater levels of enabling infrastructure investment to be undertaken.

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[1] This report does not assume that maturity is achieved only when the costs of new technology achieve 'grid parity', because this can be heavily influenced by policy decisions (e.g. subsidies).

2. The source of electricity itself can be diversified. The Government has previously considered options for developing renewable utility-scale generation (wind, tidal, etc.). Distributed generation via solar PVs and batteries can also play a role in the energy mix—as PV technologies continue to mature, smart meters are installed, and growing numbers of electric vehicles are available to serve as household batteries.

3. As a related point, security of supply concerns could also arise for alternative technologies in the context of Jersey. For biogases, biofuels and hydrogen, the prospect of sufficient production of energy on-Island to fully deliver decarbonisation in transport and heating is unlikely, even if the technologies become commercially competitive. This is because of limited availability of feedstock and crops for biogases and biofuels respectively, and insufficient local green power generation to meet the production needs of green hydrogen. Therefore, alternative sources of energy would have to be imported, which would bring costs of establishing a supply chain, as well as ongoing wholesale and transport costs. Fuel imports may also lead to emissions in the transport process.

4. There is a high degree of uncertainty around which of the three technologies will become the dominant alternative to fossil fuels in the long run—and the answer might differ by region and use case. In the short term, all sustainable fuels that are available locally—mainly biogas and biofuels—can contribute to reducing Jersey's carbon footprint.

5. In the transport sector, electrification is likely to become the dominant technology in lightweight vehicle use and short-distance goods transport. This applies to passenger cars on Jersey, where average journeys are short, and could become a solution for short-haul flights and ferries in the long term. Heavy goods and long-distance transport, however, are not necessarily fit for electrification, and are therefore more likely to depend on other forms of energy in the long term.

    a. In the short term, there is a role for liquefied biofuels—biodiesel and bioethanol, to blend with diesel and petrol respectively—in the transition phase towards carbon neutrality. This is because low-content biofuel blends can be used with existing infrastructure and appliances to immediately reduce (albeit not eliminate) carbon emissions.

    b. In the longer term, biogas (or biomethane) can provide a valuable solution for decarbonising heavy goods vehicles (HGVs), which are not suitable for electrification due their loading requirements. Local biogas production is a 'no regrets' strategy, as parts of Jersey's transport could be fuelled with compressed natural gas (CNG) irrespective of what will emerge as the global winner in zero carbon HGV fuels.

    c. Hydrogen, too, might be an alternative for HGVs, aviation and shipping in the long term. Indeed, a high level of investment and experimentation in the use of hydrogen for transport is being undertaken. Both hydrogen and biogas could become the long-term steady-state solution for heavy goods transport, depending on cost developments (in production and supply chains) and the availability of each. The role of hydrogen in the long run is likely to be focused on hard-to-electrify sectors because of the lower energy efficiency (i.e. high conversion losses) of hydrogen use.

6. In the heating sector, air source heat pumps have the great advantage of being very efficient: from one unit of energy input, they can produce three

units of useable heat output. For the transition towards a net zero future, however, other considerations are as follows.

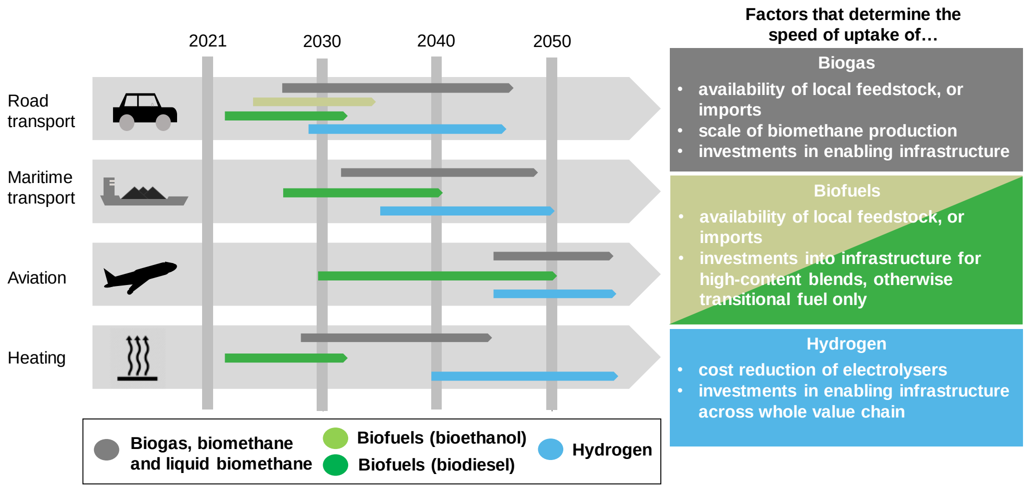
a. Biogas (or biomethane) can help to cut emissions from heating in buildings with natural gas. However, the limited gas grid in Jersey—and the distribution of liquefied petroleum gas rather than natural gas—reduces the immediacy and cost-effectiveness with which biogas or biomethane could be substituted for gas on the Island.

b. In heating, specific biodiesel blends have been encouraged as a low-cost method of reducing carbon emissions for households with oil-fired boilers. This is because existing boilers can be safely used with some biodiesel blends of up to 30%. This reduces, rather than eliminates, emissions and is therefore a transitional measure. Moreover, when evaluating the cost of biofuel boilers, one needs to consider that they have much lower efficiency than air source heat pumps and therefore need more fuel—i.e. are more costly to run—in the long term.

c. Hydrogen might be a solution to heating in the long term, but the technology has not yet been proven to be commercially viable on a large scale. Significant investments in the infrastructure at all levels of the supply chain would be necessary to switch to hydrogen as a main heating source.

The figure below provides a visual summary of the maturity of the three groups of energy source—biogas and biomethane, biofuels, and hydrogen—in the transport and heating sectors respectively. We also set out the factors that determine the speed of take-up for each of these.

Timescales for prospective maturity of fossil fuel alternatives in transport and heating



Note: In referring to maturity of technology, the focus is on when large-scale commercial deployment could be possible. The question of when a certain technology will become mature to the point of having large-scale commercial deployment potential is path-dependent, and can be influenced heavily by policy decisions and subsidies.

Source: Oxera analysis.

1 Introduction

In May 2019, the States Assembly of Jersey approved a proposition to declare a state of climate emergency, and recommended amending the 2014 Energy Plan to set a new net zero target by 2030:[2]

> Jersey should aim to be carbon neutral by 2030 and the Council of Ministers is accordingly requested to draw up a plan to achieve this, for presentation to the States by the end of 2019.

In response to the request from the Council of Ministers, the Government of Jersey produced a new 2030 Carbon Neutral Strategy.[3] This strategy document, which was approved in early 2020, set out a 'people-powered' approach, giving the population a voice over when and how Jersey should become carbon neutral. In order to hear the views of relevant stakeholders, the Government called a Citizens' Assembly, which was given the opportunity to respond to the Carbon Neutral Strategy.

In light of the Citizens' Assembly recommendations, the Government of Jersey has now commissioned Oxera to evaluate the maturity, economic viability, and roll-out conditions of multiple decarbonisation technologies—biogas and biomethane, liquefied biofuels, and hydrogen.

To provide this evaluation, this report is structured as follows:

- section 2 presents background information regarding the potential for decarbonising the Jersey economy;
- section 3 assesses the viability of biogas and biomethane in decarbonising heating and transport;
- section 4 evaluates the viability of liquefied biofuels in the decarbonisation of heating and transport;
- section 5 reviews the viability of hydrogen in the heating and transport decarbonisation pathway;
- section 6 concludes.

At this stage, the Government has asked Oxera to undertake a general review of the role that the low-carbon technologies could play in the decarbonisation of transport and heating, with reference to international precedent. Nonetheless, where our research shows that island-specific conditions are likely to facilitate or hamper the roll-out of the technologies in Jersey, we have highlighted these factors so that further feasibility analysis can be better tailored to addressing Jersey's constraints.

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[2] See Government of Jersey (2019), 'Tackling the Climate Emergency', July.

[3] Oxera has worked with the Government since 2019 in the context of developing Jersey's Carbon Neutral Strategy. Two of the main Oxera reports are the following. First, 'Carbon neutrality by 2030' (the 'Oxera October 2019 report'), which assesses international precedent for tackling the two majority sources of emissions in Jersey: road transport and the heating of buildings. Second, 'Quantitative analysis of carbon neutrality by 2030' (the 'Oxera January 2020 report'), which quantifies policy options that were shortlisted by Oxera and the Government of Jersey, for the electrification of transport and heating on the island.

2 Background

Since the declaration of a climate emergency by Jersey's States Assembly in May 2019, the Government of Jersey has been working on the development of a strategy to make Jersey carbon neutral by 2030.[4] Besides electrification, there are several established and emerging technologies that are being deployed in various countries, or being evaluated as options to decarbonise road, maritime and air transport as well as heating. This report evaluates the maturity,[5] economic viability and roll-out conditions of biogas and biomethane, liquefied biofuels and hydrogen in the heating and transport sectors. The question of when these three sustainable alternatives to fossil fuels will become commercially attractive is determined partly by governments directly setting the enabling policies in terms of carbon pricing, taxation and subsidies. Table 2.1 provides a brief definition of these three alternative fuels.

Table 2.1 Definition of biogases, biofuels and hydrogen

Technology	Definition
Biogases	
Biogas	Gaseous fuel, especially methane, produced by the fermentation of organic matter
Biomethane	Purified biogas
Liquefied biomethane	Biomethane cooled down to a liquid state
Biofuels	
Bioethanol	Ethanol produced from plants such as sugar cane or maize, used as an alternative to petrol
Biodiesel	Diesel produced from plants or waste material, used as an alternative to diesel and heating oil
Hydrogen	
Grey hydrogen	Hydrogen produced using natural gas (without carbon capture)
Blue hydrogen	Grey hydrogen where carbon is captured
Green hydrogen	Hydrogen produced via electrolysis where electricity comes from low-carbon sources

Source: Oxera analysis.

Figure 2.1 below shows the framework through which we conduct our assessment. We examine the changes that need to happen upstream, midstream and downstream by asking:

- where and how is the energy produced and sourced?
- how is the energy transported to final consumers?
- do final consumers need to change their appliances to process the energy?

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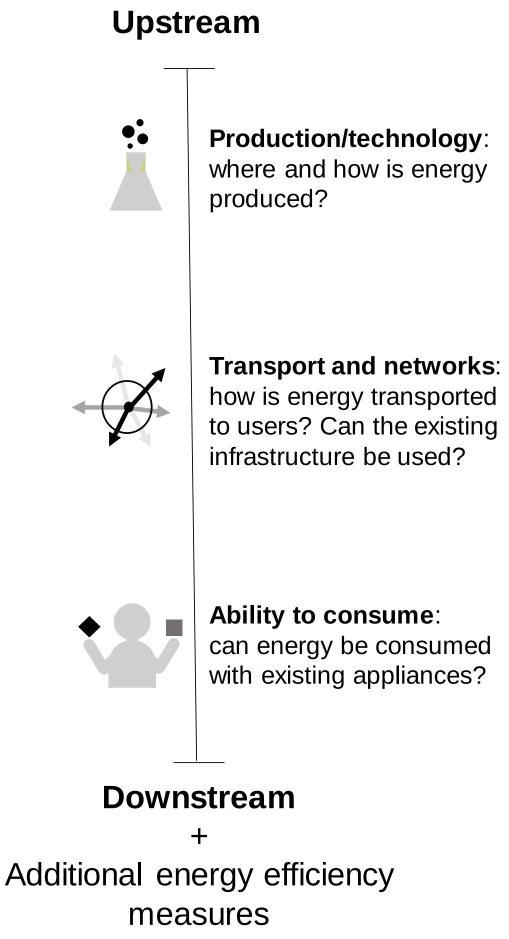
[4] The Carbon Neutral Strategy as articulated by the States of Jersey defines its net zero target in the following terms. 'Net zero' (or 'carbon-neutral') is defined as balancing the direct on-island carbon emissions, as well as the emissions arising from the generation of any imported energy, against any activity that captures, absorbs or reduces global emissions so that they are exactly offset. See Government of Jersey (2019), 'Tackling the Climate Emergency', July, section 2.1 a.

[5] Throughout this report, unless specified otherwise, 'maturity' refers to the point in time when large-scale commercial deployment could be possible.

Box 2.1 Aspects that are relevant for innovation in the context of transport and heating



Upstream

Production/technology: where and how is energy produced?

Transport and networks: how is energy transported to users? Can the existing infrastructure be used?

Ability to consume: can energy be consumed with existing appliances?

Downstream
+
Additional energy efficiency measures

Source: Oxera.

Previous analysis has revealed that the vast majority of emissions—nearly 90%—originate from transport (road, air and marine) and heating.[6] At present, Jersey is in a uniquely advantageous situation with respect to electrifying its transport and heating sectors. Through the interconnector with France, Jersey has access to sufficient low-carbon power to electrify the sectors that contribute most to the island's carbon footprint.[7] The low-carbon power imports from France have the benefit of being steady because they are produced mainly by nuclear power plants instead of intermittent sources such as wind and solar.

Relying entirely on electricity imports from France, however, carries certain security of supply risks. To diversify its energy mix, Jersey could consider other sources of large-scale generation. Jersey's location and geography provide access to renewable energy sources. In particular, it has a tidal bay that could be suitable for energy generation,[8] a high coastline-to-land ratio—which is relevant for offshore wind production—and more hours of sunshine than anywhere in the UK.

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[6] See Figure 1.1 in the Oxera October 2019 report.

[7] The imported electricity comes from low-carbon sources—namely, nuclear (65%) and hydro-electric (35%) sources in France. See Jersey Electricity (2019), 'Jersey: a low carbon island', 10 January, accessed 1 September 2021.

[8] Albeit large-scale tidal generation is in limited deployment worldwide, not least because of the costs of tidal generation engineering projects.

These characteristics could present opportunities for *tidal, off-shore wind and solar* renewable energy generation, subject to technological limitations, economies of scale and the network expenditure that may be required to integrate a high degree of renewables. Investing in on-Island renewable energy would bring new opportunities for employment and R&D. Nonetheless, the price at which electricity can be imported means that there has been no business case to date for developing on-Island utility-scale electricity generating facilities.

Distributed generation[9] in the form of solar PV and batteries could also play a role in a diversified and less import-dependent energy mix. A decarbonisation plan involving electrification of the Jersey economy does not preclude a role for decentralised electricity production. Household-level solar PVs could reduce the use of transmission-connected power, which is beneficial from a security of supply and energy independence perspective. Furthermore, with a roll-out of smart meters and rising levels of electric vehicle uptake, the batteries of electric vehicles could act as electrical storage at the household level.

The uptake of solar PVs at a household level, however, needs to be carefully managed. In particular, feed-in-tariffs (FITs) need to take into account the cost of exporting electricity to the grid. FITs may be too generous and, depending on tariff design, network charges might be bypassed by households that have the economic resources to install solar PVs—leaving a higher share of grid costs to be borne by households without the means to fund PV installation.

In summary, it is worth noting at the outset that while the focus of research in this report is alternatives to electricity, a diversification of the sources of low-carbon electricity generation would also address security of supply risks. We now turn to the examination of the alternative technologies.

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[9] Another form of decentralised energy production on the Island could be electricity generation from stored biogas (if biogas is produced in Jersey—see section 3.3).

3 Biogas, biomethane and liquefied biomethane for use in transport and heating

The opportunity for biogas and biomethane globally lies at the intersection of two of today's greatest challenges: dealing with the rising volumes of organic waste, and the need to reduce carbon emissions in all areas of our economies. By turning waste into a renewable energy resource, the production of biogas or biomethane offers the possibility to recycle resources while meeting increasing energy demands—all in an environmentally friendly way.[10]

Biogas and biomethane are different products with different applications, but they both originate from organic feedstocks whose potential is underutilised today. In the production process, organic waste materials such as crop residues, animal manure, municipal forest waste and forestry residues, and waste water are converted into biogas and biomethane via a process called anaerobic digestion (AD). As biogas and biomethane are produced from renewable sources that capture carbon dioxide when growing, these sustainable fuels do not produce any net emissions over their lifecycle.

- **Biogas (BG)** is a gaseous mixture of methane, carbon dioxide and other gases which can be used to meet heating demand. Biogas offers a sustainable solution where access to the grid does not exist or where heating demand cannot be met by carbon-neutral electricity.

- Biogas can be upgraded to **biomethane (BM)** by removing the carbon dioxide and other impurities.[11] Biomethane has similar properties to natural gas and can therefore be transported and used in the same way. Use cases include cooking, heating, transport and electricity generation.[12] Biomethane can be taken directly off pipelines or local production facilities for usage in cars that run on compressed natural gas (CNG).

- Biomethane can also be liquefied, producing **liquefied biomethane (LBM)**, also known as Bio-LNG. The advantages are that it can be transported relatively easily by trucks and dispensed directly to vehicles that run on liquefied natural gas (LNG) or CNG. The main disadvantage is that LBM needs to the cooled down to -160 degrees, which uses a lot of energy and makes it more expensive than biomethane.[13] Liquefied biomethane can be stored in, and used by, the same infrastructure as LNG.[14]

Sections 3.1 to 3.3 examine the maturity, economic viability and roll-out conditions for biogas and biomethane as an option for decarbonisation. We conclude that BG, BM and LBM could play a role in decarbonising transport and heating in the medium term. The big advantage of this technology is that it can generally be used with the existing natural gas infrastructure upstream,

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[10] See International Energy Agency (2020), 'Outlook for biogas and biomethane: Prospects for organic growth', March.

[11] Biomethane can also be produced by gasifying solid biomass—see Li, H., Mehmood, D., Thorin, E. and Yu, Z. (2017), 'Biomethane Production Via Anaerobic Digestion and Biomass Gasification', May.

[12] The greenhouse gas reduction potential of biomethane is twofold: on the one hand, it can abate the carbon that would have been emitted if natural gas had been used; and on the other hand, it can remove the methane emissions that would have resulted from the waste decomposition.

[13] See Nachtmann, K., Baum, S., Fuchsz, M. and Falk, O. (2017), 'Efficient storage and mobile use of biogas as liquid biomethane', *Landtechnik*, **72**, pp. 179–201.

[14] See Urban, W. (2013), 'Biomethane injection into natural gas networks', *The Biogas Handbook*, Woodhead Publishing, pp. 278–403; Bhatia, S. (2014), 'Biogas', chapter 17 in Bhatia, S. (ed.), *Advanced Renewable Energy Systems*, WPI Publishing, pp. 426–472; International Energy Agency (2020), 'Outlook for biogas and biomethane: Prospects for organic growth', March.

midstream and downstream.[15] If this infrastructure is in place, BG, BM and LBM can therefore be a low-cost way of decarbonising sectors that are hard to electrify, such as HGVs and maritime transport.

3.1 Maturity of technology

In considering the maturity of biogas and biomethane, all levels of the supply chain must be taken into account. The **upstream process** of producing biogas and biomethane via AD or gasification is already technologically well established. The amount of feedstock that is theoretically available for producing biogas and biomethane is large and distributed widely across the planet, but only a small share of this potential is being currently exploited. The International Energy Agency ('IEA') has found that 20% of today's worldwide gas demand could be met with biogas and biomethane if existing resources were fully exploited.[16]

The production of BG and BM is expected to grow significantly over the coming years: between 2018 and 2030, demand for these low-carbon gases is set to rise by 182% to 468% depending on the decarbonisation scenario considered.[17] Similarly, manufacturing of LBM is expected to advance by more than 600% in the next three years.

Midstream, the transportation and storage of biogas, biomethane and its liquid counterpart is technologically well established, as the existing natural gas and LNG infrastructure can be used.[18] In fact, biomethane is injected into the UK natural gas grid today.[19]

Downstream, BG, BM and LBM have widespread use cases in road and maritime transport as well as heating.

- In *road transport*, the technology to use biomethane in gaseous form, or in liquefied form, is well established. It is, however, not necessarily compatible with existing petrol or diesel engines, and therefore requires moderate retrofitting. It can be used directly as a gas in surface CNG vehicles and as a liquid in road and maritime LNG vehicles—but these constitute only a small (although growing) share of the vehicle stock. Due to the limited number of CNG and LNG vehicles, the fuelling network is just being developed: Europe's gas fuelling station network has recently reached the milestone of 4,000 CNG and 400 LNG stations.[20]
- In *maritime transport*, first trials using LBM are also being run today.[21] It is being used as 'drop-in fuel' for ships which run on LNG, with the option of retrofitting ships that run on other fuels. LBM can be a low-carbon

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[15] It is important to note that a key use case for biomethane—as an immediate blend in the natural gas grid for heating—is not applicable to the Jersey context because Jersey has a limited gas network, and transports liquefied petroleum gas instead of natural gas (see section 3.3).

[16] Existing resources here are waste products and land that is readily available, and do not include land currently used for agriculture or other purposes. If agricultural land were converted to produce feedstock, the supply of biogas and biomethane could be even higher. See International Energy Agency (2020), 'Outlook for biogas and biomethane: Prospects for organic growth', March.

[17] See International Energy Agency (2020), 'Outlook for biogas and biomethane: Prospects for organic growth', March.

[18] For more information on the transportation and storage of biogas, biomethane and bio-LNG, see Sustainable conversation 'Biomethane report, Chapter 4', accessed 4 September 2021.

[19] Department of Energy & Climate Change (2009), 'Biomethane into the Gas Network: A Guide for Producers', December.

[20] NGVA Europe (2021), 'NGVA Europe has published 2020 gas vehicle statistics and Europe has reached a new gas refuelling infrastructure milestone', press release, 29 April, accessed 4 September 2021.

[21] For instance, in Finland—see Bioenergy News (2020), 'Finnish firms testing liquefied biogas as shipping fuel', 12 June.

alternative to both LNG and heavy fuel oil (HFO)—LNG vessels have 35% lower emissions than HFO-fuelled vessels when using normal LNG,[22] and the reduction is around 92% when using Bio-LNG.[23] Despite this great potential, the use of LBM in maritime transport today remains limited.

- Some *heating* sectors have started using biomethane through the existing natural gas networks where these are available. Biomethane can also be used as a direct substitute in traditional gas boilers suited to natural gas. (It is worth noting in the Jersey context, however, that a single gas pipeline network does not currently extend across the island. See section 3.3.)

Box 3.1 At a glance: maturity by value chain segment—biogas, biomethane and liquefied biomethane

Upstream: feedstock is widely available and production technology is well established.

Midstream: current natural gas infrastructure can be used without retrofitting.

Downstream: in transport, current appliances can be used, but engine retrofitting may be required as well as investment in fuelling stations; in heating, natural gas infrastructure can be used without retrofitting.

Note that these comments on using natural gas infrastructure with biogas and biomethane are based on international experience; in Jersey, LPG is used instead of natural gas, which implies additional investments in the supply chain, to adapt it to the use of biogases. This is explained in section 3.3.

Source: Oxera analysis.

Given the technological maturity of biogas, biomethane and LBM in the heating and transport sectors, the following section examines the economic viability of this technology.

3.2 Economic viability of the technology

Upstream, the price of biogas and biomethane depends on the production process, but is generally higher than the prevailing natural gas prices in different regions.[24] The IEA estimates that the average price for biogas produced today is around USD 16 per million British thermal units (MMBtu) in Europe, which is significantly above the price of natural gas—which averaged between around 1.5 to 6 USD per MMBtu in 2020.[25] The natural gas price in Europe has climbed to around 15 USD per million MMBtu lately, increasing the competitiveness of biogas.[26]

However, as production technologies progress, carbon prices rise and economies of scale set in, the economic viability of biogas and biomethane production is expected to improve. In the long run, biogases are expected to be commercially competitive with other green fuels such as green hydrogen.[27]

At the **downstream** level, additional costs generally increase significantly when new appliances need to be purchased and installed. However, biogas, biomethane and LBM have the great advantage that most existing vehicles can

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[22] Ricardo Energy & Environment (2016), 'The role of natural gas and biomethane in the transport sector', February.

[23] European Biogas (2020), 'BioLNG in Transport: Making Climate Neutrality a Reality', November.

[24] See International Energy Agency (2020), 'Outlook for biogas and biomethane: Prospects for organic growth', March.

[25] For the biogas price in Europe, see International Energy Agency (2020), 'Outlook for biogas and biomethane: Prospects for organic growth', March, p. 31. For the natural gas price, see YCharts (2021), 'European Union Natural Gas Import Price', accessed 4 September 2021.

[26] See YCharts (2021), 'European Union Natural Gas Import Price', accessed 4 September 2021.

[27] SEA-LNG (2020), 'Availability and costs of liquefied bio- and synthetic methane – the maritime shipping perspective', 20 March.

be retrofitted, and no investment into the existing gas infrastructure is needed. Therefore, these sustainable fuels have a favourable business case in helping economies to decarbonise.

Box 3.2 At a glance: economic viability by value chain—biogas, biomethane and LBM

Upstream: biogas production is more expensive than natural gas production, but cost decreases are possible. In the long run, biogases are expected to be commercially competitive with other emerging technologies such as green hydrogen.

Midstream: no investment into natural gas infrastructure is needed.

Downstream: limited switching cost as natural gas appliances can be used.

Note that these comments on using natural gas infrastructure with biogas and biomethane are based on international experience; in Jersey, LPG is used instead of natural gas, which implies additional investments in the supply chain, to adapt it to the use of biogases. This is explained in section 3.3.

Source: Oxera analysis.

3.3 Access and conditions for roll-out

To roll out biogas and biomethane in the transport and heating sectors, a certain set of infrastructure needs to be available at all levels of the supply chain. In practice, the following conditions must be met in Jersey.

- **Upstream**: biogas or biomethane must be produced in Jersey, or imported. Local production is preferable from a sustainability perspective, as transporting the sustainable gas could lead to additional emissions. Currently, Jersey does not have any biomethane production facilities, but a feasibility study into the creation of an anaerobic digestion plant in Jersey has been conducted. The study found that sufficient livestock on Jersey existed to run a medium-sized AD plant which could produce biogas for electricity generation, heating and transport.[28] The output generated from the plant would be sufficient to fuel Jersey's Technical and Transport Services, which run 43 regular buses per year.[29] The volumes of biogas that could be locally produced therefore appear to be insufficient to fully decarbonise heat and transport on the island. This means that additional biogas and biomethane would need to be imported, or other sources of energy would need to be added to the mix.[30] Still, local biogas production is a 'no regrets' strategy, as parts of Jersey's transport could be fuelled with biomethane irrespective of what eventually becomes the dominant technology on a global scale.

- **Midstream**: to use biomethane and bio-LNG for transport, CNG and LNG refuelling stations need to be available. Currently, no such fuelling stations seem to be available on the island.[31] To use biomethane for heating in an efficient way, biomethane-compatible gas networks must be available. Jersey's current gas network is used to transport LPG. Jersey Gas has previously stated that the existing system would not be suitable for

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[28] ADAS UK Ltd. (2013), 'Feasibility Study into Establishing an Anaerobic Digestion Plant using Substrates from Agriculture Sectors on Jersey', December.

[29] ADAS UK Ltd. (2013), 'Feasibility Study into Establishing an Anaerobic Digestion Plant using Substrates from Agriculture Sectors on Jersey', December.

[30] Imports would need to be brought in liquefied form (i.e. LBM) to an import terminal or through a pipeline to France. Both options are costly and would have poor economies of scale due to limited demand in Jersey.

[31] Desk research has returned no results when searching for the availability of CNG/LNG fuels in Jersey. The fuels also do not seem to be stocked by Channel Island Fuels, Jersey Gas or Rubis, according to a review of the companies' websites.

biomethane injection.[32] Biogas or biomethane could, however, be compressed in tanks or high-pressure bottles and distributed around the island.

- **Downstream**: no biomethane- or LBM-compatible road or shipping vehicles seem to be available in Jersey at present.[33] This means that existing vehicles would need to be retrofitted or new vehicles would need to be purchased. In heating, Jersey currently runs mainly on LPG- and oil-fired boilers. These would need to be replaced or retrofitted to run on biomethane.[34]

Box 3.3 At a glance: roll-out considerations—biogas, biomethane and LBM

Upstream: limited biogas production feasible in Jersey—probably most useful for decarbonisation of HGVs.

Midstream: existing LPG distribution infrastructure can probably not be used, but appropriate vehicles could be directly fuelled at a local biomethane production facility (if it existed).

Downstream: moderate investments into existing appliances to be compatible with CNG/LNG are needed.

Source: Oxera analysis.

In sum, the technology is well established, and likely to become more cost-competitive as the cost of carbon increases; also, there is some potential to produce biogas on Jersey. However, as the potential for local production is limited, the cost and carbon footprint of imports would have to be evaluated. Moreover, in order to embrace biogas, biomethane and LBM on the island, investments into retrofitting transport vehicles and heating appliances would need to be made.

3.4 Conclusion

The production and use of biogas and biomethane bring benefits from reduced emissions, improved waste management and greater resource efficiency. The technology for producing these sustainable fuels is well established, and sufficient feedstock is theoretically available, but it is commercially unattractive at the current time. Reductions in the cost of production in the coming years could, however, turn biogas and biomethane into valuable parts of the energy mix. In particular, they could play an important role in decarbonising parts of our economies that are hard to decarbonise otherwise, such as heavy goods vehicles and maritime transport.

One of the greatest benefits of biogas and biomethane is that they can utilise the existing natural gas network, thereby allowing for the continued use of such sunk capital assets. However, if there is not a widespread natural gas network, and/or final appliances are not compatible with biogas and biomethane—as is the case in Jersey—significant investments in the midstream and/or downstream market are due.

Table 1.1 below summarises our findings in terms of the maturity, cost-effectiveness and roll-out conditions for biogas, biomethane and LBM as a

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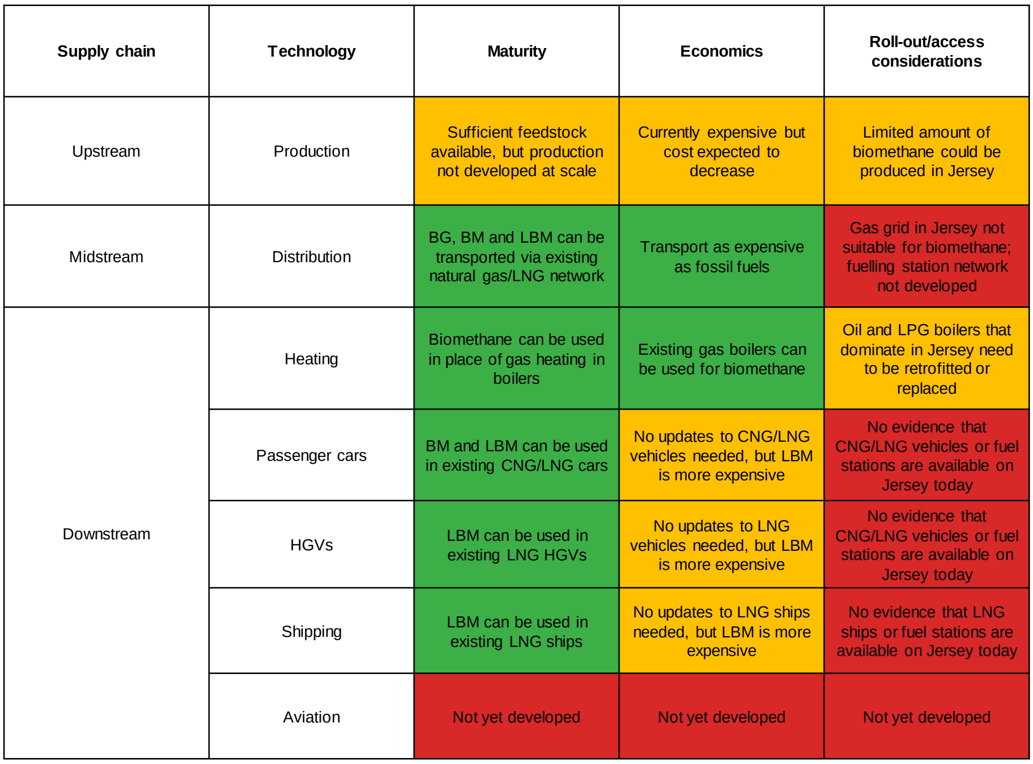
[32] ADAS UK Ltd. (2013), 'Feasibility Study into Establishing an Anaerobic Digestion Plant using Substrates from Agriculture Sectors on Jersey', December, p. 13.

[33] See Aukevisser, 'World Fleet of LNG Carriers > 75.000 m3', accessed 4 September 2021.

[34] Changes to the existing heating technology might be disruptive and might involve changes to boilers, hot water tanks, radiators, etc.

means to decarbonise. It portrays the current situation—i.e. how available, cost-effective and accessible the respective technologies are today.

Table 3.1 Viability of biogas, biomethane and LBM for near-term use in heating and transport



Supply chain	Technology	Maturity	Economics	Roll-out/access considerations
Upstream	Production	Sufficient feedstock available, but production not developed at scale	Currently expensive but cost expected to decrease	Limited amount of biomethane could be produced in Jersey
Midstream	Distribution	BG, BM and LBM can be transported via existing natural gas/LNG network	Transport as expensive as fossil fuels	Gas grid in Jersey not suitable for biomethane; fuelling station network not developed
Downstream	Heating	Biomethane can be used in place of gas heating in boilers	Existing gas boilers can be used for biomethane	Oil and LPG boilers that dominate in Jersey need to be retrofitted or replaced
	Passenger cars	BM and LBM can be used in existing CNG/LNG cars	No updates to CNG/LNG vehicles needed, but LBM is more expensive	No evidence that CNG/LNG vehicles or fuel stations are available on Jersey today
	HGVs	LBM can be used in existing LNG HGVs	No updates to LNG vehicles needed, but LBM is more expensive	No evidence that CNG/LNG vehicles or fuel stations are available on Jersey today
	Shipping	LBM can be used in existing LNG ships	No updates to LNG ships needed, but LBM is more expensive	No evidence that LNG ships or fuel stations are available on Jersey today
	Aviation	Not yet developed	Not yet developed	Not yet developed

Note: The table's colour-coding works as follows: 'green' means no or very few reservations, 'amber' means some reservations, and 'red' means major reservations. 'BG' refers to biogas, 'BM' refers to biomethane, 'LBM' refers to liquefied biomethane, 'CNG' refers to compressed natural gas, and 'LNG' refers to liquefied natural gas.

Source: Oxera analysis.

4 Liquefied biofuels for use in transport and heating

Biofuels are fuels that are produced from organic matter, including corn and starch, vegetable oils, or waste and debris. Made from plants which take in carbon as they grow, they are associated with reduced carbon emissions relative to the fossil fuels that they replace. They can be used in both transport and heating, either in pure form or blended with fossil fuels. In general, the more highly concentrated blends are able to reduce greenhouse gas emissions to a greater extent: the higher the concentration of biofuel, the higher the reduction in greenhouse gas emissions.

The two most mature and commonly used biofuels are as follows.

- **Bioethanol** can be used in petrol-fuelled vehicles. Most commonly used in the blended form E10, which contains 10% bioethanol, it can also be used as a blend of up to E85, and is particularly well suited to fuelling road vehicles.[35] Pure bioethanol has the potential to reduce emissions by between 19% and 62% depending on the feed-in stock used.[36]
- **Biodiesel** can be used in diesel-fuelled vehicles and appliances. Two types of biodiesel, FAME[37] and HVO,[38] are produced commercially on a large scale. When used neat, the reduction in carbon emissions relative to fossil diesel ranges from 41%[39] to 90%,[40] depending on the oils from which the biodiesel is made and the upstream processes involved. It is already mature for use in road transport and heating, with the potential to be scaled up in aviation and shipping in the near future.

The following sections examine the maturity, economic viability and deployment conditions for bioethanol and biodiesel as a substitute or complement to electrifying transport and heating.

We conclude that bioethanol is a well-established technology that is most suited to use in road transport. Biodiesel is also a well-established and increasingly utilised technology that can be used in transport (heavy goods, maritime and air) as well as heating. Due to their maturity and availability, biofuels could play an important role in the transition towards a low-carbon economy. Note that the role of biofuels is cited as transitional because, as

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[35] In bioethanol blends, the number usually indicates the percentage of bioethanol included. E10, for instance, contains 10% bioethanol, while E15 contains 15% bioethanol.

[36] See Wang, M., Han, J., Dunn, J., Cai, H. and Elgowainy, A. (2012), ‘Well-to-wheels energy use and greenhouse gas emissions of ethanol from corn, sugarcane and cellulosic biomass for US use’, *Environmental Research Letters*, **7**, August. Bioethanol has a lower energy density than traditional petrol, and achieves 30% fewer miles per gallon than gasoline. Due to the reduced energy density, other experts argue that the emissions savings achieved per vehicle mile are actually below the figures cited above. See Hill, J., Polasky, S., Nelson, E., Tilman, D., Huo, H., Ludwig, L., Neumann, J., Zheng, H. and Bonta, D. (2009), ‘Climate change and health costs of air emissions from biofuels and gasoline’, *PNAS*, **106**:6, February.

[37] FAME biodiesel is a biofuel produced by transesterification of fatty acids that can be blended with diesel in existing engines. See European Technology and Innovation Platform website https://www.etipbioenergy.eu/index.php?option=com_content&view=article&id=330, accessed 8 September 2021.

[38] HVO is a biodiesel produced through the hydrogenation of vegetable oils and waste that can be used directly in diesel engines. See van Dyk, S., Su, J., McMillan, J.D. and Saddler, J.J.N. (2019), ‘Drop-in Biofuels: The key role that co-processing will play in its production’, *IEA Bioenergy*, January.

[39] Hill, J., Polasky, S., Nelson, E., Tilman, D., Huo, H., Ludwig, L., Neumann, J., Zheng, H. and Bonta, D. (2009), ‘Climate change and health costs of air emissions from biofuels and gasoline’, *PNAS*, **106**:6, February.

[40] Advanced Motor Fuels TCP and IEA Bioenergy (2020), ‘The Role of Renewable Transport Fuels in Decarbonizing Road Transport: Production Technologies and Costs’, November.

blends for use with existing appliances and infrastructure, biofuels can lead to a reduction in carbon emissions, but not to an elimination.

4.1 Bioethanol

Bioethanol, typically made from either corn starch or sugar cane, has been widely used as a fuel in road transport. In the USA, for instance, some 98% of petrol sold contains some volume of bioethanol.[41] In many EU countries, the standard petrol grade is already 10% bioethanol, known as E10, and this is also set to become the standard grade of petrol in the UK.[42]

4.1.1 Maturity of technology

At the **upstream** level, bioethanol is widely produced. Its most common production process is summarised in Box 4.1. Bioethanol can also be produced with an alternative process, which is less mature but has greater potential to reduce carbon emissions. This alternative production process is summarised in Box 4.2 below.

Box 4.1 Production process for bioethanol

Bioethanol is made by fermenting starch or sugar. Most bioethanol is made from corn in the USA or sugarcane in Brazil. In the USA it is typically blended with petrol in a 10% ethanol blend known as 'gasohol' (E10), whereas in Brazil it is commonly used as a 100% ethanol fuel, or 15% ethanol is blended with 85% petrol (E15). First generation ethanol is produced from food crops, whereas second generation ethanol, known as cellulosic ethanol, is derived from low-value biomass that possesses a high cellulose content, including wood chips, crop residues, and municipal waste. Bioethanol is then transported to the fuel terminal—e.g. by rail, truck or barge. Low blends of ethanol, including E10, can be stored and transported with existing infrastructure, and E15 can also be transported and stored with some modern equipment. Higher blends up to E85 require special considerations relating to storage, handling and transportation.

Source: Britannica website, https://www.britannica.com/technology/biofuel, accessed 7 September 2021; Searle, S., Sanchez, F.P., Malins, C. and German, J. (2014), 'Technical Barriers to the Consumption of Higher Blends of Ethanol', 4 February.

Midstream, bioethanol is also well established as regards transport and storage technologies. The vast majority of equipment, including storage tanks, pipes and vehicle engines, is already compatible with low blends of bioethanol up to E10, and some equipment designed for use with traditional petrol and E10 is also suitable for E15.[43] Higher blends of bioethanol—above E15—have higher barriers to usage. Due to material incompatibility, such as corrosion of steel and water contamination, pipelines typically have to be replaced or lined.

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[41] See US Department of Energy: Alternative Fuels Data Center website, https://afdc.energy.gov/fuels/hydrogen_production.html, accessed 7 September 2021.

[42] See *Jersey Evening Post* (2020), 'Government set to bring in E10 fuel to tackle emissions', 4 March.

[43] Searle, S., Sanchez, F.P., Malins, C. and German, J. (2014), 'Technical Barriers to the Consumption of Higher Blends of Ethanol', 4 February.

Box 4.2 Alternative lower-carbon sources of bioethanol

Cellulosic bioethanol refers to bioethanol produced from cellulose contained in plant-based materials, including corn, wheat and straw, and agricultural and municipal waste. While this form of bioethanol production is not yet commercially mature, it is capable of greatly reduced carbon intensity compared with petrol (i.e. 88–108% reduction), comparing favourably to corn-based bioethanol, which sees reductions of around 34%. Cellulosic bioethanol is expected to be a necessary component in meeting various state and national renewable fuel standards.

Source: Wang, M., Han, J., Dunn, J., Cai, H. and Elgowainy, A. (2012), 'Well-to-wheels energy use and greenhouse gas emissions of ethanol from corn, sugarcane and cellulosic biomass for US use', *Environmental Research Letters*, **7**, August.

Downstream, bioethanol's main use is in road transport, where it can be blended with petrol in varying quantities. It is currently unsuitable for use in other modes of transport, such as maritime and aviation, although it has the potential to replace the lead additives in small planes in future.[44] Recently, the development of multi-fuel engines in shipping has meant that oil, gas and alcohols can be used in ships' engines.[45] The use of bioethanol in shipping may therefore grow in the long run as more multi-fuel engines are introduced. In heating, bioethanol is not widely used, and its primary use is for bioethanol fires.[46]

Box 4.3 At a glance: maturity by value chain—bioethanol

Upstream: the bioethanol production process is well established and bioethanol can be produced from feedstocks including corn and sugarcane.

Midstream: low bioethanol blends up to E15 can be transported and stored with existing infrastructure; higher bioethanol needs some modifications to be transported and stored.

Downstream: low bioethanol blends up to E15 can be used in existing vehicles manufactured after 2001; higher bioethanol blends require flexible fuel vehicles to be used.

Source: Oxera analysis.

4.1.2 Economic viability of technology

In transitioning from the use of traditional petrol to bioethanol, investments at the upstream, midstream and downstream level might be needed. The cost of producing bioethanol depends on the feedstock used and varies by region. In 2017, bioethanol was produced at similar prices to gasoline in Brazil, and slightly higher prices than gasoline in the USA.[47]

Equipment used in the transport and distribution of petrol is compatible with low-concentration bioethanol up to E10, and some is compatible with the use of E15; indeed, E10 is increasingly a standard petrol grade in Europe. This implies that no investments are needed at the **midstream** level. For higher-content blends, additional investments into storage, dispensing, handling, and vehicle operation are likely to be needed.[48]

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[44] Searle, S., Sanchez, F.P., Malins, C. and German, J. (2014), 'Technical Barriers to the Consumption of Higher Blends of Ethanol', 4 February.

[45] Hsieh, C.C. and Felby, C. (2017), 'Biofuels for the marine shipping sector', *IEA Bioenergy*, October.

[46] Ryšavý, J., Horák, J., Kuboňová, L., Hopan, F., Krpec, K., Kubesa, P., Molchanov, O. and Ochodek, T. (2020), 'Real Operating Parameters of Bioethanol Burners in Terms of Heat Output', *ACS omega*, **5**:44, pp. 28587–96.

[47] International Energy Agency (2020), 'Biofuel and fossil-based transport fuel production cost comparison, 2017', 7 January.

[48] As an example, bioethanol separates when it comes into contact with water in a process known as phase separation, so sludge clearance is required in storage tanks. E85 can also cause corrosion of some soft metals and reduce tensile strength of some non-metallic materials, so storage facilities may need to be

For low-concentration bioethanol blends, switching costs at the **downstream** level are low because existing vehicles, tanks and dispensers can be reused. For higher concentrations, investments into retrofitting vehicles, tanks and dispensers may be needed.[49] High ethanol blends are not suitable for use in normal road vehicle engines due to high temperatures and material incompatibility. Since fewer miles per gallon can be travelled with bioethanol than with petrol, larger fuel tanks are typically needed. Flexible fuel vehicles (FFVs), specially designed to cope with high bioethanol blends, include automobiles, buses and minivans.[50]

Box 4.4 At a glance: economic viability by value chain—bioethanol

Upstream: bioethanol production cost depends on the feedstock used and varies by region.

Midstream: low switching costs for low-concentration bioethanol because existing infrastructure can be used; limited investments necessary for higher bioethanol blends.

Downstream: small switching costs for low-concentration bioethanol because existing appliances can be used; investments into appliances necessary for higher bioethanol blends.

Source: Oxera analysis.

4.1.3 Access and conditions for roll-out

Upstream, Jersey currently does not produce its own bioethanol, but imports it from Europe. Switching from traditional petrol to bioethanol therefore does not affect the current level of supply security in Jersey. By growing oilseed rape, wheat and barley, Jersey could potentially be producing bioethanol in the future.

However, much of the agricultural land on Jersey—apart from that growing grass and forage crops—is planted with high-value crops of potatoes, fruit or vegetables, which return gross margins approximately ten times larger than the potential returns of crops grown for bioethanol.[51] Given this large disparity in returns, replacing these valuable crops with bioethanol crops is unlikely to be a viable option. Waste potatoes could potentially be used as a feedstock for bioethanol production in the future, but volumes are unlikely to meet local demand.[52]

In terms of **midstream and downstream** roll-out, bioethanol requires few adjustments to infrastructure and vehicles for low blends up to E15.[53] Higher blends require infrastructure and road vehicles to be updated or retrofitted, and therefore have a higher cost and greater timeframe for roll-out. Nevertheless, the timeframe to resolve issues that could arise in roll-out is short compared with a transition towards electrification and hydrogen. Table 4.1 below

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adapted. See U.S. Department of Energy (2016), 'Handbook for Handling, Storing and Dispensing E85 and Other Ethanol-Gasoline Blends', February.

[49] National Renewable Energy Authority (2008), 'Cost of adding E85 equipment to existing gasoline stations: NREL Survey and Literature Search', March.

[50] FFVs require few modifications compared with normal vehicles and are only US$70–US$100 more expensive to manufacture than an equivalent model of a non-FFV. Vehicles can also be retrofitted to make them suitable for high bioethanol blend usage. See Searle, S., Sanchez, F.P., Malins, C. and German, J. (2014), 'Technical Barriers to the Consumption of Higher Blends of Ethanol', 4 February; Woodall, B. (2010), 'GM seeking more U.S. bioethanol fuelling stations', *Reuters*, 16 February; US Department of Energy: Alternative Fuels Data Center website, https://afdc.energy.gov/vehicles/flexible_fuel.html, accessed 7 September 2021.

[51] See AEA Energy & Environment (2007), 'Development of Jersey Energy Policy', March.

[52] See AEA Energy & Environment (2007), 'Development of Jersey Energy Policy', March.

[53] All infrastructure and most cars can safely be used with E10, which is the standard petrol grade in most countries. All vehicle models after 2001 and some newer models of fuel dispenser can also be used with E15 without modifications.

summarises the technological barriers and time to solution for the different bioethanol blends.

Table 4.1 Barriers to uptake of bioethanol in the transport sector

Equipment	Problem	Solution for E10	Solutions for E25–E85	Timeframe for resolving issues
Road vehicles	Increased temperatures and pollutants in exhaust, material incompatibility and leakage	Unlikely to have problems, avoid fuelling older vehicles with E20	FFVs must be used, or existing vehicles must be retrofitted, with added cost	Immediate for E10–E20; days to months for E25–E85
Motorcycles, boats and small engines	Increased temperatures and pollutants in exhaust, material incompatibility and leakage	New vehicles and machines should be designed for E15 upwards	No clear solution	Not advised to fuel these vehicles and machines on ethanol in the near term
Maritime transport	Incompatible with diesel engines of large and very large ships	Increase production of new ships with multi-fuel engines	Increase production of new ships with multi-fuel engines	Many years; not viable in the near term
Aviation	*Incompatible with aviation engines*			
Fuel storage tanks and dispensers	Material incompatibility	Retrofit dispensers and clean tanks	Retrofit or replace equipment	Hours to days for retrofitting; days to months for replacement
Pipelines	Corrosion of steel and water contamination	No modifications needed up to E15; for higher blends add inhibitors to fuel	Add liners to the inside of pipelines or possibly build new pipelines	Months to three years

Source: Searle, S., Sanchez, F.P., Malins, C. and German, J. (2014), ‘Technical Barriers to the Consumption of Higher Blends of Ethanol’, 4 February.

The box below summarises the conditions for the roll-out of bioethanol.

Box 4.5 At a glance: roll-out considerations—bioethanol

Upstream: low-volume bioethanol production on Jersey is possible, but this would displace more valuable agricultural crops, and supply would be unlikely to meet local demand.

Midstream: existing petrol fuel storage tanks and dispensers on Jersey need to be retrofitted or replaced for higher bioethanol blends.

Downstream: existing petrol vehicles on Jersey need to be retrofitted or replaced for higher bioethanol blends.

Source: Oxera analysis.

4.2 Biodiesel and sustainable aviation fuels

Biodiesel is made from vegetable oils, most commonly soybean, palm and rapeseed, as well as waste oils. Sustainable aviation fuels (SAFs) are biofuels for aeroplanes, which can reduce carbon emissions relative to regular fuel by between 20% and 90%, with the potential to reduce up to 100% in future.[54] There are two commonly used types of biodiesel and one sustainable aviation fuel produced on a large scale.

- **FAME biodiesel** is the most widely used biodiesel. It is most commonly used as a blended fuel, with 7–30% biodiesel blended with fossil diesel.[55] For a greater impact on reducing carbon emissions, B100, or neat biodiesel, can be used.
- **HVO biodiesel** is less common, but growing in popularity due to its lower carbon intensity. Depending on the feedstock, it can reduce carbon emissions relative to regular diesel by 90%.[56]
- **HEFA-SPK** is the most technically mature and commercially viable of the five SAFs currently produced.[57] It can reduce CO_2 emissions from aeroplanes by between 18% and 69% depending on the feedstock.[58]

The following sections discuss the suitability of biodiesel and SAFs for complementing, or replacing, fossil diesel in transport and heating.

4.2.1 Maturity of technology

This section assesses the maturity of biodiesel in the upstream, midstream and downstream segments of its value chain. Both biodiesel variants, FAME and HVO, and have well-established **upstream** production processes.[59]

Biodiesel is most mature for consumption by diesel-consuming *road vehicles*, which is where the vast majority of biodiesel is used.[60] FAME biodiesel blends have long been used across various jurisdictions, including the USA. Demand for HVO has recently grown in markets such as California, British Columbia, Germany and Sweden, where policies incentivise the use of low-carbon fuels. Biodiesel is particularly relevant for the decarbonisation of *HGVs*, for which the UK government expects a take-up to around 10% by 2030 and 15–20% by 2040.[61]

Aviation is another sector of the economy in which liquid biofuels can play an important role in decarbonisation. At present just one SAF, known as HEFA-SPK, is commercially viable and produced at a larger scale. It can be mixed with regular aviation fuels up to a 50–50 blend for use in existing engines.[62] The demand for HEFA-SPK and other SAFs is expected to grow significantly

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[54] Bauen, A., Bitossi, N., German, L., Harris, A. and Leow, K. (2020), 'Sustainable Aviation Fuels: Status, challenges and prospects of drop-in liquid fuels, hydrogen and electrification in aviation', *Johnson Matthey Technology Review*, **64**:3, pp. 263–78.
[55] These blends are called B7, B10, B20 and B30 depending on the biodiesel concentration.
[56] See Neste website, https://www.neste.com/products/all-products/base-oils#a9dd8077, accessed 4 September 2021.
[57] International Energy Agency (2019), 'Are aviation biofuels ready for take-off?', 18 March.
[58] Bosch, J., De Jong, S., Hoefnagels, R. and Slade, R. (2017), 'Aviation biofuels: strategically important, technically achievable, tough to deliver', *Grantham Institute at Imperial College London*, November.
[59] FAME biodiesel is produced via a process called transesterification, which describes the pre-treatment of vegetable oils and their acid esterification. About 36bn litres of biodiesel per year are produced globally using this process. HVO biodiesel is produced via the treatment of vegetable oils with hydrogen. Over the past few years, interest has grown in HVO due to its usefulness as a 'drop-in fuel' with low carbon-intensity. As of 2018, 25 plants existed globally for its production—four of these in the EU—and there are plans to build more. Today, around 6.5bn litres of HVO are produced annually. See Advanced Motor Fuels TCP and IEA Bioenergy (2020), 'The Role of Renewable Transport Fuels in Decarbonizing Road Transport: Production Technologies and Costs', November.
[60] See U.S. Energy Information Administration website, https://www.eia.gov/energyexplained/biofuels/use-of-biodiesel.php, accessed 4 September 2021.
[61] UK Climate Change Committee (2020), 'Sixth Carbon Budget: Surface Transport', December.
[62] IRENA (2017), 'Biofuels for Aviation', January.

over the coming years: SAFs are expected to reach around 10% of aviation fuel demand by 2030, and close to 20% by 2040.[63] Pure biofuel planes are likely to be available within the next decade or two.[64] The main barriers to commercial maturity include the need to advance jet systems, raise fuel-blending requirements, and obtain safety certification from global regulators.[65]

Similarly, biofuels are considered to be a relevant option to decarbonise *maritime transport*.[66] Biodiesel can already be used as a replacement or blend in maritime vehicles without modifications to the engine.[67] Unlike light road transport, heavy road transport as well as shipping and aviation cannot be electrified at a significant level and are likely to continue to depend on low-carbon liquid or gaseous fuels.

The main challenge to using biofuels in maritime and air transport are the large volumes of fuel needed.[68] A single very large ship may consume 100m litres of biofuel in a year, which is the annual production of a single medium-size production facility.[69] Aviation and maritime transport compete for the valuable biofuel: both use biodiesel from plant-based oils, of which only 10–20 megatons can be produced per year with current technology.[70]

In *heating*, FAME biodiesel blends have been encouraged as a low-cost of method of reducing carbon emissions for households with oil boilers in the UK.[71] Existing boilers can be safely used with biodiesel blends of up to 30%, which helps reduce carbon emissions by about 26%.[72] While pure biodiesel can cut emissions by about 94%, it cannot run on existing boilers and requires a boiler replacement.[73] These biodiesel-compatible boilers, however, are available for sale today.

To conclude, biodiesel is a well-established technology that is being used today. The slightly more nascent HVO biodiesel has a better carbon footprint and is therefore the more promising technology in road and maritime. In aviation, one SAF which is relatively mature (HEFA-SPK) exists and is used in blends to fuel aeroplanes today. The main challenge for more widespread use of biodiesel and SAFs are their limited production and thereby availability for use in transport vehicles.

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[63] International Energy Agency (2019), ‘Are aviation biofuels ready for take-off?’, 18 March.

[64] Trials are already being conducted today: in 2018, Boeing flew a commercial airliner on 100% biofuel for the first time. The company aims to start delivering commercial planes flying on 100% biofuel by 2030. See Cramer, D. (2020), ‘Hydrogen-powered aircraft may be getting a lift’, *Physics Today*, 1 December, p. 27; *The Guardian* (2021), ‘Boeing says it will make planes able to fly on 100% biofuel by 2030’, 23 January.

[65] *The Guardian* (2021), ‘Boeing says it will make planes able to fly on 100% biofuel by 2030’, 23 January.

[66] Lifetime greenhouse gas emissions (g/MJ of energy) are reduced by around 77% when maritime vehicles run on pure HVO compared to heavy fuel oil. See Hsieh, C.C. and Felby, C. (2017), ‘Biofuels for the marine shipping sector’, *IEA Bioenergy*, October.

[67] Smaller machines are able to run on pure biodiesel, while larger engines can run only on blends. It is theoretically possible to run engines on 100% FAME biodiesel, although this may require modifications to the engines and permissions from the manufacturer. Various initiatives have been put in place to explore the viability of biofuels in shipping. For instance, the US Navy and the Great Green Fleet have sought to provide half of the navy’s power from renewable sources including biofuels by 2020. See Alexander, D. (2016), ‘Great Green Fleet using biofuels deployed by U.S. Navy’, *Reuters,* 21 January; Hsieh, C.C. and Felby, C. (2017), ‘Biofuels for the marine shipping sector’, *IEA Bioenergy*, October.

[68] Hsieh, C.C. and Felby, C. (2017), ‘Biofuels for the marine shipping sector’, *IEA Bioenergy*, October.

[69] Hsieh, C.C. and Felby, C. (2017), ‘Biofuels for the marine shipping sector’, *IEA Bioenergy*, October.

[70] Hsieh, C.C. and Felby, C. (2017), ‘Biofuels for the marine shipping sector’, *IEA Bioenergy*, October.

[71] Bentley, R. (2019), ‘Households who use heating oil should be preparing to transition to biofuel, says industry body’, *East Anglian Times*, 22 June.

[72] Bentley, R. (2019), ‘Households who use heating oil should be preparing to transition to biofuel, says industry body’, *East Anglian Times*, 22 June.

[73] Bentley, R. (2019), ‘Households who use heating oil should be preparing to transition to biofuel, says industry body’, *East Anglian Times*, 22 June.

Box 4.6 At a glance: maturity by value chain—biodiesel

Upstream: the biodiesel production process is well established for both FAME biodiesel and HVO, which can be made from plant oils and waste oils.

Midstream: low FAME blends and HVO can be transported and stored with existing infrastructure; higher FAME blends require infrastructure adjustments.

Downstream: low FAME blends and HVO can be used in existing vehicles; higher FAME blends require adapted vehicles.

Source: Oxera analysis.

4.2.2 Economic viability of the technology

In assessing the economic viability of biodiesel, the cost of production or importation, transportation and storage, and of the appliances that are able to utilise biodiesel, need to be taken into account. **Upstream**, biodiesel is more expensive to produce or import than fossil diesel. In aviation, for example, SAFs are estimated to be between 58% and 69% more expensive than normal aviation fuel.[74] In the shipping sector, biofuels cost between 87% and 300% more depending on the type of biodiesel used.[75]

An additional challenge is that the price of biodiesel is closely linked to the price of the feedstock, which can lead to volatility. In recent years, the price of feedstock has increased—pushing the price of biodiesel up.[76] Biodiesel produced from agricultural waste, which has a better carbon footprint, is unlikely to be commercially competitive against conventional fuels in the short run.[77]

Midstream and downstream, the economic viability of biodiesel depends on the use case. Table 4.1 below summarises the compatibility of biodiesel with the existing infrastructure, and shows where larger investments are needed.

Table 4.2 Investments needed for usage of biodiesel and SAFs

Equipment	Compatibility
Diesel road vehicles	**FAME** can be used in low concentrations with existing engines, although higher concentrations require replacement or retrofitting. **HVO** can be used directly as a drop-in fuel.
Maritime transport	**HVO** and **FAME** are compatible with diesel engines of large and very large ships, which are typically blended into ship fuel.
Aviation	**SAFs** are compatible with engines of commercial jets up to a 50% blend. Possible to use in 100% concentration in some jets, but modifications are required.
Heating	**FAME** and **HVO blends** can be used in existing boilers, but transitioning to pure biodiesel requires investments in new boilers.
Fuel storage tanks and dispensers	**FAME** can be used in existing storage tanks and dispensers in low concentrations. In high concentrations, tanks may have to be replaced or retrofitted. **HVO** is suitable to use in fuel storage tanks and dispensers without changes needed.

Source: Oxera.

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[74] European Aviation Safety Agency website, www.easa.europa.eu/eaer/topics/sustainable-aviation-fuels/bio-based-aviation-fuels, accessed 4 September 2021.

[75] Hsieh, C.C. and Felby, C. (2017), 'Biofuels for the marine shipping sector', *IEA Bioenergy*, October.

[76] For example, between 2005 and 2012 feedstock costs for biodiesel increased by 87% for soybean and 49% for rapeseed oil. See IRENA website, https://www.irena.org/costs/Transportation/Biodiesel, accessed 4 September 2021.

[77] See Advanced Motor Fuels TCP and IEA Bioenergy (2020), 'The Role of Renewable Transport Fuels in Decarbonizing Road Transport: Production Technologies and Costs', November.

In *road transport*, pure FAME biodiesel would require investments into new infrastructure. Given that the technology does not serve to reach full carbon neutrality, this money could be invested in technologies which are able to achieve full carbon neutrality instead. HVO biodiesel, in contrast, can be used in existing vehicles and therefore has very low switching costs, making it an economically viable transition fuel for road transport. In *aviation and shipping*, no investments are needed for using blends of biodiesel, therefore making this a valuable transition fuel.

In *heating*, switching to biodiesel blends comes at no cost, as existing boilers can be used—but transitioning to pure biodiesel requires investments in new boilers. Biodiesel blends might therefore provide an economical way of reducing emissions from heating in the short term, particularly for lower-income households that have not yet transitioned to heat pumps. When evaluating the cost of biofuel boilers, one needs to consider that they have a much lower efficiency than heat pumps (84% vs 300%)[78] and therefore require more fuel to run. Even though the fixed cost of a biofuel boiler might be lower, its levelised cost of energy is higher than that of an air source heat pump.[79]

Box 4.7 At a glance: economic viability by value chain—biodiesel

Upstream: biodiesel production is mostly more expensive than traditional diesel production.

Midstream: FAME requires retrofitting; HVO does not.

Downstream: limited investments into appliances needed.

Source: Oxera analysis.

4.2.3 Access and conditions for roll-out

Upstream, biodiesel was produced locally in Jersey between 2007 and 2010. The island generated approximately 200 tonnes of biodiesel from waste cooking oil each year, which was available for purchase by local bulk fuel users such as haulage and transport companies.[80] Today, all of Jersey's biodiesel is imported.

In *road transport*, Jersey is well placed to switch to HVO biodiesel, as no changes to the existing infrastructure are needed. Indeed, the first HVO biodiesel (RD100) has been recently introduced in Jersey by Rubis. Trials to use RD100 in Jersey's fleet of heavy goods vehicles are currently taking place with the aim of being rolled out more extensively.[81] While cost is limited, the benefits of switching include up to 90% reduction in carbon intensity of biodiesel-fuelled road vehicles.

Jersey is also well placed to use biodiesel in place of *heating* oil. With a non-negligible share of households still using heating oil, a switch to biodiesel blends has the potential to reduce emissions at low cost.[82] In the long run, the inability of biodiesel to reduce emissions to zero because blends are used and the associated cost of replacing boilers to use high-biodiesel blends might make heat pumps the preferred option to decarbonise heating.

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[78] See Table B3.3 in UK Climate Change Committee (2020), 'Sixth Carbon Budget: Surface Transport', December.

[79] See Table M3.2 in UK Climate Change Committee (2020), 'Sixth Carbon Budget: Surface Transport', December.

[80] Government of Jersey (2007), 'Local biodiesel goes into production', 3 October.

[81] See Rubis website, https://rubis-ci.co.uk/motor-and-aviation/rd100/, accessed 4 September 2021.

[82] In Jersey, 30% of households relied on oil heating in 2012. See Jersey Competition Regulatory Authority (2012), 'Review of the supply of heating oil in Jersey', February.

Box 4.8 At a glance: roll-out considerations—biodiesel

Upstream: low-volume production of biodiesel from waste materials possible on Jersey, but insufficient to satisfy local demand.

Midstream: HVO can be rolled out to existing diesel road vehicles immediately on Jersey.

Downstream: biodiesel blends can be rolled out to existing oil boiler users on Jersey.

Source: Oxera analysis.

4.3 Conclusion

The use of sustainable biofuels has the potential to reduce transport and heating emissions in the short and medium term. The largest caveat to the roll-out of biofuels is that most of them cannot reduce emissions to zero and can therefore at best be useful as a transitional source of energy. The following bullets provide a summary.

- *Bioethanol's* greatest potential lies in substituting petrol in road transport in the short term. The use of bioethanol blends cannot deliver zero emissions, but it can help reduce emissions from road transport at a relatively low cost. Higher bioethanol blends, particularly E85 and pure bioethanol, have the potential to further reduce carbon emissions, but come at the cost of widespread replacement of engines and vehicles. Bioethanol has limited relevance at present for other areas of transport and heating.
- *Biodiesel's* greatest potential lies in the reduction of emissions in road transport in the short and medium term, and maritime and aviation in the medium to long term. Take-up of high-biodiesel blends and pure biodiesel has increased significantly in recent years and could play an important role in decarbonising heavy goods and maritime transport. In aviation, *sustainable aviation fuels* have great potential in significantly reducing carbon emissions. Heavy goods, maritime and air transport vehicles cannot currently be electrified to a significant extent and are likely to continue to depend on low-carbon liquid or gaseous fuels into the medium and long term.

The table below summarises our findings in terms of the maturity, cost-effectiveness and access conditions of biofuels as a means to decarbonise. It portrays the current situation—i.e. how available, cost-effective and accessible the respective technologies are today.

Table 4.3 Viability of biofuels for near-term use in heating and transport

Supply chain	Technology	Maturity	Economics	Roll-out/access considerations
Upstream	Production	Bioethanol and biodiesel produced at scale	Price depends on cost of feedstock	Bioethanol and biodiesel possible to produce in Jersey and widely available to import
Midstream	Distribution	Bioethanol and biodiesel can be transported by road, rail and ship. For FAME and bioethanol, some modifications are needed	Transport is not much more costly than fossil fuels	Small investments and retrofitting of distribution infrastructure needed for FAME and bioethanol
Downstream	Heating	Biodiesel can be used in place of oil heating in boilers	Existing boilers can be used for low biodiesel blends. Boiler replacements needed for higher biodiesel blends	Fuel is widely available. Boiler replacements likely to be costly and less efficient than heat pumps
	Passenger cars	Low bioethanol blends widely used in existing cars	No updates to vehicles needed for low bioethanol blends. Flexible fuel vehicles are needed for higher bioethanol blends	Bioethanol readily available but must be imported, E10 sold by most garages
	HGVs	FAME and HVO are widely used in diesel engines. Large emission reductions possible with HVO	FAME requires compatible vehicles for higher blends but HVO can be used as a drop-in fuel	RD100 available at fuelling stations in Jersey and has already been trialled
	Shipping	FAME or HVO can be blended with heavy fuel oil in diesel engines of large ships	Existing engines can be used but challenges around cost and availability of fuels	Large quantities of biodiesel must be imported
	Aviation	HEFA-SPK can be blended with kerosene in existing aeroplane engines	Existing engines can be used but challenges around cost and availability of fuels	Large quantities of HEFA-SPK must be imported

Note: The table’s colour-coding works as follows: ‘green’ means no or very few reservations, ‘amber’ means some reservations, and ‘red’ means major reservations.

Source: Oxera analysis.

5 Hydrogen for use in transport and heating

Hydrogen is a non-toxic, odourless, and highly combustible gas. Its molecular properties mean that it can be used in a variety of industry sectors and—crucially—it produces zero carbon emissions when burned. It is the most abundant chemical substance in the universe, but in order to use it as a fuel or heat source, it usually needs to be produced using a chemical reaction.[83]

The most established methods to produce hydrogen are colour-coded as follows.[84]

- **Grey hydrogen**: most hydrogen today comes from natural gas, which is bonded with carbon and can be separated from it via a process called steam methane reforming (SMR). However, the excess carbon generates CO_2. This hydrogen is called 'grey' whenever the excess CO_2 is not captured.[85]
- **Blue hydrogen**: hydrogen is considered 'blue' whenever the emissions generated from SMR are captured and stored underground via industrial carbon capture and storage (CCS), so that these are not dispersed in the atmosphere. Because of the CCS technology involved, blue hydrogen is currently more expensive to produce than grey hydrogen. To deliver against decarbonisation objectives, the use of blue (rather than grey) hydrogen is required.
- **Green hydrogen**: hydrogen can also be produced via a process called water electrolysis—i.e. using electricity to decompose water into hydrogen gas and oxygen. If the electricity used is generated from renewables, it is carbon-free and therefore is categorised as 'green'.[86] Today, less than 0.1% of global dedicated hydrogen production comes from water electrolysis.[87]
- **Pink hydrogen**: pink hydrogen is hydrogen produced via electrolysis using nuclear power instead of renewables.

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[83] White & Case LLP (2020), 'Hydrogen's new dawn', https://www.whitecase.com/publications/alert/hydrogens-new-dawn, accessed 30 August 2021.

[84] Giovannini, S. (2020), '50 shades of (grey and blue and green) hydrogen', 13 November, https://energy-cities.eu/50-shades-of-grey-and-blue-and-green-hydrogen/, accessed 30 August 2021; White & Case LLP (2020), 'Hydrogen's new dawn', https://www.whitecase.com/publications/alert/hydrogens-new-dawn, accessed 30 August 2021.

[85] An alternative classification system based on the EU hydrogen strategy calls grey hydrogen 'fossil based hydrogen' and green hydrogen 'renewable or clean hydrogen'. The EU strategy captures blue and pink hydrogen under 'low carbon hydrogen', which includes fossil-based hydrogen using carbon capture and electricity-based hydrogen with significantly reduced full life-cycle greenhouse gas emissions compared to existing hydrogen production. See European Commission (2020), 'A hydrogen strategy for a climate-neutral Europe', July, pp. 3–4.

[86] Alkaline electrolysers are the most mature electrolysis technology; these dominate the market, especially for large-scale projects. However, many new projects are now opting for polymer electrolyte membrane (PEM) designs, which can operate more flexibly and are therefore more compatible with variable renewable electricity generation. In addition, projects involving high-efficiency solid oxide electrolyser cells (SOECs) are also beginning to be announced, nearly all of them in Europe to produce synthetic hydrocarbons. See International Energy Agency (2020), 'Hydrogen tracking report', June.

[87] International Energy Agency (2019), 'The future of hydrogen', June.

Box 5.1 Alternative production processes for hydrogen

There are a number of alternative, less frequent ways to produce hydrogen that go beyond the ones outlined above. Examples include (i) renewable liquid reformation, by which renewable liquid fuels, such as ethanol, are reacted with high-temperature steam to produce hydrogen near the point of end-use; (ii) fermentation, by which biomass is converted into sugar-rich feedstocks that can be fermented to produce hydrogen; and (iii) pyrolysis, by which hydrogen is produced from the heat-driven decomposition of methane into hydrogen and carbon in solid form.

Other hydrogen production methods are currently still under development, including (i) high-temperature water splitting, which uses high temperatures generated by solar concentrators or nuclear reactors to drive chemical reactions that split water to produce hydrogen; (ii) photobiological water splitting, which uses microbes such as green algae that consume water in the presence of sunlight to produce hydrogen as a by-product; and (iii) photoelectrochemical water splitting, which employs photoelectrochemical systems to produce hydrogen from water using special semiconductors and energy from sunlight.

Source: US Department of Energy: Alternative Fuels Data Center website, https://afdc.energy.gov/fuels/hydrogen_production.html, accessed 7 September 2021; Florence School of Regulation (2021), 'Between Green and Blue: a debate on Turquoise Hydrogen', 18 March.

Most of the hydrogen today is used either in the petrochemicals industry, where it is used to split heavier oils into lighter petroleum products, or to produce ammonia for fertilisers.[88] Similar to biogas and biofuels, its largest potential, however, is believed to lie in to hard-to-decarbonise sectors such as heavy goods vehicles (HGVs), aviation, shipping and heating applications.[89] In addition to being used directly in fuel cells and boilers, hydrogen could in future serve as the main input for synthetic fuels. Box 5.2 below describes how this process could look.

Box 5.2 Hydrogen as an input for synthetic fuels

Synthetic fuels—also called eFuels—could be used in maritime, air and road transport in the form of gasoline, diesel, gas or kerosene. Synthetic fuels are not yet a well-established technology, and years (or even decades) are needed before they can become established. The processing facilities today are exceedingly expensive, and there are only a few test plants that can produce this innovative fuel.

The production process works as follows: in a first stage, green hydrogen is produced from water via electrolysis with renewable energy. Carbon is added to this to produce a liquid fuel. This carbon can be recycled from industrial processes or captured using CCS technologies. Combining carbon and hydrogen then results in the synthetic fuel, which could be used in existing combustion engines and distributed via the current filling-station network. Once mature, synthetic fuels could significantly reduce the carbon-intensity of gasoline- and diesel-powered transport, and thus make a significant contribution to reaching net zero.

Source: Bosch website, https://www.bosch.com/stories/synthetic-fuels/, accessed 7 September 2021.

The following sections examine the maturity of hydrogen for heating and transport (section 5.1), its economic viability (section 5.2), and its conditions for roll-out (section 5.3). The conclusion (section 5.4) contains a high-level assessment of the role of hydrogen in Jersey's carbon neutral strategy.

5.1 Maturity of technology

When assessing the maturity of hydrogen, factors at all levels of the supply chain—upstream, midstream and downstream—need to be taken into account.

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[88] White & Case LLP (2020), 'Hydrogen's new dawn', https://www.whitecase.com/publications/alert/hydrogens-new-dawn, accessed 30 August 2021.

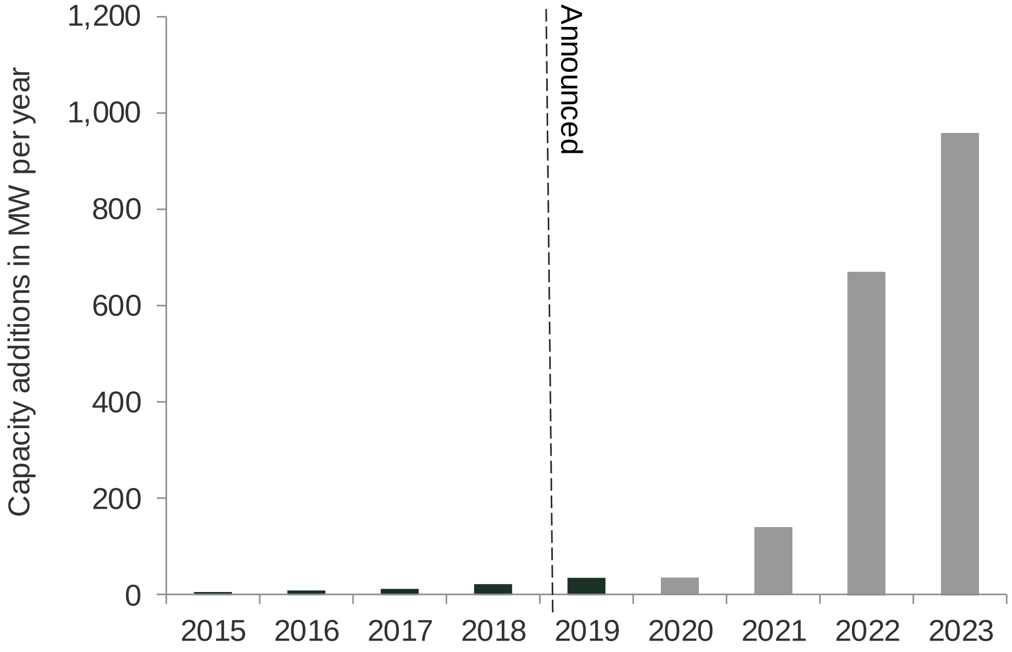
[89] IRENA (2019), 'Hydrogen: A renewable energy perspective', September.

In order for the technology to develop its full potential and be commercially deployed at large scale, all parts of the supply chain must be fully mature.

At the **upstream** level, specific hydrogen production technologies are well established. The large majority of hydrogen developed today (about 95%),[90] however, comes from fossil fuels, which is not necessarily carbon-neutral. According to estimates by the IEA, less than 0.1% of hydrogen produced today is green.[91]

In order to produce green hydrogen at scale, three key inputs are needed: (i) large amounts of water; (ii) carbon-free electricity; and (iii) electrolysers. While green hydrogen production capacity has increased slowly in the past, progress is expected to pick up sharply in the next two years. According to the IEA hydrogen project database, 670MW and 960MW of electrolysis capacity is expected to come online in 2022 and 2023 respectively (see Figure 5.1). In line with this growth, low-carbon hydrogen production is set to triple from 0.36Mt in 2019 to 1.45Mt in 2023.[92]

Figure 5.1 Global electrolysis capacity becoming operational annually, 2015 to 2023, historical and announced



Source: Oxera based on IEA hydrogen project database (2020).

One of the greatest challenges with hydrogen remains transporting it to where it is needed. **Storing and transporting** the highly combustible gas is not easy: it takes up large amounts of space and requires a converted pipe network as its transport tends to make steel pipes and welds prone to failure. The bulk of hydrogen transport will require dedicated pipeline networks—which would be costly to build—pressurising the gas, or cooling it to a liquid for transport via ships.

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[90] IRENA, 'Hydrogen from renewable power', https://www.irena.org/energytransition/Power-Sector-Transformation/Hydrogen-from-Renewable-Power, accessed 4 September 2021.
[91] IRENA, 'Hydrogen from renewable power', https://www.irena.org/energytransition/Power-Sector-Transformation/Hydrogen-from-Renewable-Power, accessed 4 September 2021.
[92] International Energy Agency (2020), 'Low-carbon hydrogen production, 2010-2030, historical, announced and in the Sustainable Development Scenario, 2030', 9 June.

Midstream, hydrogen is currently distributed via three methods.

- **Pipeline**: this least-expensive way (in terms of average costs) to deliver large volumes of hydrogen for heating is seen as having great potential in many countries where there is a widespread natural gas network that may be repurposed. However, as set out in section 5.3, this is less likely to be an option for Jersey given the limited gas grid infrastructure on the island.
- **High-Pressure Tube Trailers**: transporting compressed hydrogen gas by truck, rail, ship or barge in high-pressure tube trailers is expensive and is used primarily for distances of 200 miles or less. This could be an option for Jersey, as distances on the island are generally short.
- **Liquefied Hydrogen Tankers**: cryogenic liquefaction is a process that cools hydrogen to a temperature where it becomes a liquid.[93] Although the liquefaction process is expensive, it enables hydrogen to be transported more efficiently over longer distances. Assuming that hydrogen is produced on the island, long-distance transport would not be needed, but it may be a relevant consideration if hydrogen is imported for use in Jersey.[94]

Because hydrogen is difficult to transport, it is currently best used close to where it is produced. Building a new hydrogen pipeline network involves high initial capital costs, and hydrogen's properties present unique challenges to pipeline materials and compressor design. Using hydrogen in transport further requires a network of hydrogen fuelling stations, which are currently being developed in some countries such as Japan or Germany.[95]

To use hydrogen in transport and heating, additional technologies are needed to transform hydrogen for use with appliances in the **downstream market**:

- **fuel cells** are needed to transform hydrogen into electricity to move cars and other vehicles;
- **hydrogen boilers** are needed to transform hydrogen into heat.

Some of these enabling technologies are well established as well, but maturity varies depending on the specific application. In the transport sector, a small number of *passenger cars* that utilise hydrogen fuel cells are available for sale today.[96] Currently, the USA is leading in terms of fuel cell electric vehicle (FCEV) stock on the road, followed by China, Japan and South Korea. Approximately 23,000 FCEVs were deployed in 2019, with an increasing trend.[97]

Heavy goods vehicles and buses with hydrogen fuel cells are currently reaching commercial maturity. The total number of heavy goods buses and trucks in use at the end of 2019 is estimated to be around 6,300.[98] An even smaller number of HGVs with hydrogen fuel cells are available, and many car

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[93] Liquefied hydrogen adds a layer of complexity. If the liquefied hydrogen is not used at a sufficiently high rate at the point of consumption, it boils off (or evaporates) from its containment vessels. As a result, hydrogen delivery and consumption rates must be carefully matched.

[94] However, the means of transport may then itself involve carbon emissions. Importing hydrogen would furthermore require the construction of an import terminal, which may not be economical due to the limited demand in Jersey.

[95] International Energy Agency (2020), 'Hydrogen tracking report', June.

[96] See H2 website, https://h2.live/en/wasserstoffautos/, accessed 4 September 2021.

[97] International Energy Agency (2020), 'Hydrogen tracking report', June.

[98] Oxera analysis based on International Energy Agency (2020), 'Hydrogen tracking report', June.

manufacturers are still trialling the technology.[99] Several truck manufacturers have announced plans to develop models and begin deploying units in Europe and Japan. The potential is seen in a partnership between Hyundai and H2 Energy, which aims to deploy 1,600 hydrogen HGVs in Switzerland by 2025.[100] The infrastructure to fuel FCEVs is also currently being developed. According to IEA estimates, around 470 hydrogen refuelling stations were in operation worldwide at the end of 2019—most of them located in Japan, Germany and the USA.[101] According to the UK Sixth Carbon Budget, 11 hydrogen refuelling stations were in operation in the UK, with a further five planned.

Hydrogen-powered ships have been trialled by market leaders such as CBM in Belgium, but have yet to be developed for large-scale commercial use. Experiments are being conducted in Japan, where a larger hydrogen-fuelled ferry was set to launch in early 2021, and France, where the world's first commercial cargo transport vessel is scheduled for delivery in September this year.[102] Hydrogen is seen as one of the most promising zero-emission technologies in *aviation*, but is years from reaching commercial deployment.[103]

In the *heating* sector, household appliances for hydrogen are currently being developed. Industry leaders are making progress with their prototypes and testing of hydrogen boilers. The UK Hydrogen Strategy lays out that the first homes with hydrogen boilers in the UK will be built in Gateshead.[104] At the same time, as part of the National Grid Hydrogen Project, a town in Scotland will become the first location in the UK where hydrogen appliances will be trialled in over 300 homes and fed with hydrogen gas directly from the grid.[105]

In summary, zero-carbon hydrogen has been identified as critical for meeting net zero, particularly in 'hard to electrify' UK industrial sectors. However, the production, distribution and downstream appliances that enable the use of hydrogen in heating and transport are largely immature today. At all levels of the supply chain, hydrogen still needs to be developed for commercial use at large scale. Below, we turn to the economic viability of using hydrogen in the decarbonisation of heating and transport.

Box 5.3 At a glance: maturity by value chain—hydrogen

Upstream: the large majority of hydrogen developed today (about 95%) comes from fossil fuels, which are not necessarily carbon-neutral; less than 0.1% of hydrogen produced today is green. Accordingly, green hydrogen has yet to be commercially deployed at scale.

Midstream: hydrogen networks do not yet exist at a large scale.

Downstream: small amounts of fuel-cell vehicles are commercially sold; engines and appliances are being developed for use in heavy goods transport, shipping and heating.

Source: Oxera analysis.

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[99] See Hyundai website, https://hyundai-hm.com/en/, accessed 4 September 2021; Commercial Fleet website, https://www.commercialfleet.org/news/truck-news/2020/09/17/daimler-trucks-to-launch-hydrogen-fuel-cell-hgv-1, accessed 4 September 2021.

[100] UK Climate Change Committee (2020), 'Sixth Carbon Budget: Surface Transport', December.

[101] International Energy Agency (2020), 'Hydrogen tracking report', June.

[102] Timperley, J. (2020), 'The fuel that could transform shipping', *BBC*, 30 November; Ovcina, J. (2021), 'Flagships set to debut world's 1st hydrogen-powered commercial cargo ship', *Offshore Energy*, 7 April.

[103] See Airbus website, https://www.airbus.com/newsroom/stories/hydrogen-aviation-understanding-challenges-to-widespread-adoption.html, accessed 8 September 2021.

[104] HM Government (2021), 'UK Hydrogen Strategy', August, p. 83.

[105] See Chapter 1 in HM Government (2021), 'UK Hydrogen Strategy', August.

5.2 Economic viability of technology

To evaluate the cost of hydrogen for heating and transport, investments at all levels of the supply chain need to be taken into account. **Upstream**, the production cost of green or pink hydrogen is determined by the renewables/nuclear electricity price, the investment cost of the electrolyser, and its operating hours. As of today, green hydrogen is two to three times more expensive than blue hydrogen, produced from fossil fuels in combination with carbon capture and storage (CCS).[106]

However, the cost of green and pink hydrogen is expected to drop significantly in the coming years, and is expected to be competitive with natural gas by 2050 in most parts of the world on an energy-equivalent basis. The cost drop is driven mostly by the reduced cost and increased availability of electrolysers. Between 2014 and 2019, the cost of electrolysers produced in North America and Europe fell by 40%, according to a recent report on the hydrogen economy by BNEF—and this trend is expected to continue.[107]

In the **downstream** market, the viability of hydrogen depends on the use case.

- *Transport*: hydrogen-powered fuel cells may be more economically feasible for use in heavy transport than for passenger vehicles. Battery-powered electric cars currently dominate fuel cells in the passenger vehicle market, but hydrogen's higher energy density means that fuel cells have a power density that is greater than the lithium-ion batteries used for electric vehicles (EVs). Hydrogen's higher energy density is conducive to long-distance transport because the range of a fuel cell vehicle can be easily increased by simply adding more hydrogen tanks to the same fuel cell stack (given sufficient space), giving fuel cells a marginal cost advantage over batteries. Another consideration is weight: batteries are heavy and limit an HGV's load-carrying capacity. The same holds for maritime long-distance transport, where batteries are not an option because of their limited range and weight. Most ships could be retrofitted with hydrogen fuel cells, so no completely new assets would be required.
- *Heating*: in heating, all decarbonisation strategies include investments in isolation and energy efficiency. On top of these, most decarbonisation technologies require investments in new boiler systems.[108] Hydrogen boilers and hydrogen hybrid heat pumps have the large disadvantage of having much lower efficiency values than other heating technologies. Whereas modern electrified air-to-air and air-to-water heat pumps reach efficiency values of up to 300%, hydrogen boilers reach a maximum of around 90%.[109] This means that, while the capital expenditure (CAPEX) and operating expenditure (OPEX) of hydrogen boilers might be lower than those of heat pumps, the levelised cost of energy for hydrogen boilers is estimated to be around double that of air-to-air heat pumps by 2030.[110] In addition, the expansion of the hydrogen distribution infrastructure requires significant financial investments in upgrading the pipeline network. Because hydrogen contains less energy per unit volume than all other fuels, transporting,

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[106] See International Renewable Energy Agency (2020), 'Making Green Hydrogen a Cost-Competitive Climate Solution', 17 December.

[107] Bloomberg New Energy Finance (2020), 'Hydrogen Economy Outlook', 30 March.

[108] Nearly all gas appliances that are in use today, including boilers, are able to run on a mixture of hydrogen and natural gas of up to 20%. To move to higher hydrogen concentrations or pure hydrogen, new boiler systems are needed. See Worcester-Bosch website, https://www.worcester-bosch.co.uk/hydrogen, accessed 8 September 2021.

[109] See Table B3.3 in UK Climate Change Committee (2020), 'Sixth Carbon Budget: Buildings', December.

[110] See Table M3.2 in UK Climate Change Committee (2020), 'Sixth Carbon Budget: Buildings', December.

storing, and delivering it to the point of end-use is more expensive on a per-gasoline gallon equivalent (per-GGE) basis.

Box 5.4 At a glance: economic viability by value chain—hydrogen

Upstream: production of green hydrogen is significantly more expensive than blue hydrogen, but costs are expected to decrease.

Midstream: large investments are needed to build hydrogen networks.

Downstream: investments in hydrogen-compatible vehicles and boilers are needed.

Source: Oxera analysis.

5.3 Access and conditions for roll-out

To roll out hydrogen for transport and heating, the appropriate infrastructure needs to be available at all levels of the supply chain. In practice, this means that the following conditions must be met.

- **Upstream**: zero-carbon hydrogen production facilities must be available. This requires excess carbon-free electricity, electrolysers and water for green/pink hydrogen or steam reformation and carbon capture and storage for blue hydrogen. These sources of production are not available in Jersey today and would require significant financial investments. Alternatively, hydrogen could be imported (e.g. in liquefied form), but this transport would be expensive and the process of transport may itself involve carbon emissions. An over-reliance on imports could furthermore create risks around the security of supply for hydrogen and associated investment in the wider value chain.[111]

- **Midstream**: hydrogen distribution facilities must be available. For instance, this tends to require a hydrogen-compatible pipeline network (for heating) and hydrogen fuelling stations (for transport).
  - In the case of heating, internationally, hydrogen is being explored as an alternative to natural gas not least because there is significant sunk capital in the national gas grid. Mature gas networks generally need to be repurposed (e.g. to transport hydrogen instead of natural gas) to avoid stranding of assets. However, this is not a pressing concern in Jersey, as the Island does not have a significant proportion of households using piped gas.
  - In the case of transport, hydrogen fuelling stations are not available in Jersey today and would require significant financial investments.

- **Downstream**: hydrogen-compatible appliances must be available. In the heating sector this means hydrogen boilers; in transport it means hydrogen-compatible vehicles. Neither of these are widely available in Jersey today and would require significant financial investments.

Because changes to the infrastructure are needed upstream, midstream and downstream, a switch to hydrogen furthermore implies a significant time lag between investment decision and roll-out. Even if the decision to opt for hydrogen in heating and transport is taken today, it would take 15 to 20 years

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[111] See Chapter 1 in HM Government (2021), ‘UK Hydrogen Strategy’, August.

until the entire set-up including production (or import) facilities, grid conversion, distribution infrastructure and appliances were widely available.[112]

Box 5.5 At a glance: roll-out considerations—hydrogen

Upstream: production of green hydrogen in Jersey is theoretically possible, but requires significant investments in production facilities.

Midstream: a hydrogen network is not available on Jersey and would require considerable investments to build.

Downstream: hydrogen-compatible vehicles and boilers are not available on Jersey.

Source: Oxera analysis.

5.4 Conclusion

Hydrogen has significant potential to decarbonise our economies in the long run. In particular, hydrogen can play an important role in decarbonising sectors which are otherwise hard to decarbonise, such as heavy goods transport, shipping and aviation. In other sectors of our economy—such as private transport and heating—more cost-effective technologies such as electrification are available.

Hydrogen is particularly useful if the enabling infrastructure is already in place—i.e. if gas-fired power plants allow the attachment of CCS and SMR, or if green surplus power enables electrolysis, and a well-developed natural gas network allows for efficient transport. Neither of these conditions hold in Jersey and that makes the transition towards hydrogen less attractive. Using hydrogen for heating and private passenger cars is also less efficient than electrification, as large amounts of energy are lost during the conversion process.

Using hydrogen in heating and transport requires significant investments in the upstream, midstream and downstream market segments. Table 5.1 below summarises our findings in terms of the maturity, cost-effectiveness and access conditions for hydrogen as a means to decarbonise. It portrays the current situation—i.e. how available, cost-effective and accessible the respective technologies are today.

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[112] The only use case where hydrogen could become feasible within the next decade is road transport, where hydrogen-compatible cars are commercially available today and infrastructure investments are limited.

Table 5.1 Viability of hydrogen for near-term use in heating and transport

Supply chain	Technology	Maturity	Economics	Roll-out/access considerations
Upstream	Production	Green hydrogen being tested at scale	Electrolysers on declining cost path	Significant investment needed
Midstream	Distribution	Local hydrogen grids are being tested	Transport of hydrogen is more costly than other fuels	Large investments in distribution infrastructure needed
Downstream	Heating	Pilot projects are currently being run	Levelised cost higher than heat pumps	Boiler replacements needed
	Passenger cars	Few models are commercially available	Hydrogen cars more expensive than electric	Fuelling stations in Jersey not yet available
	HGVs	First investments in bus and truck fleets are happening	Could be more cost-effective than electricity in the long run	Fuelling stations in Jersey not yet available
	Shipping	Pilot projects are currently being run	Could be more cost-effective than electricity in the long run	Fuelling stations in Jersey not yet available
	Aviation	Not yet developed	Not yet developed	Not yet developed

Note: The table’s colour-coding works as follows: ‘green’ means no or very few reservations, ‘amber’ means some reservations, and ‘red’ means major reservations.

Source: Oxera analysis.

6 Conclusion

This report provides an assessment of the maturity, economic viability and timeframe to viability of technologies that could play a role in the decarbonisation of Jersey's transport and heating sectors. In particular, the report evaluates the role of biogas and biomethane, liquid biofuels and hydrogen along the supply chain to evaluate which investments would be needed to make these technologies feasible.

Figure 6.1 below shows which technologies are feasible today and in the medium term, with reference to international precedent.

Figure 6.1 Overall feasibility of technologies by use case

	🚗	🚚	🚢	✈	♨
Currently feasible, with reference to international precedent	• BM for LNG/CNG cars • Low-bioethanol blends for petrol cars • biodiesel blends for diesel cars • hydrogen for fuel cell cars	• biodiesel blends for diesel HGVs • BM for LNG/CNG HGVs	• biodiesel blends for diesel ships • BM for LNG ships	• biodiesel blends	• BG/BM for gas boilers • biodiesel blends for oil boilers • hydrogen blends for hydrogen-compatible boilers
Midterm feasible—i.e. 15–20 years and beyond	• Higher-bioethanol blends for retrofitted petrol cars	• hydrogen-fuelled HGVs (if enabling infrastructure investments happen)	• hydrogen-fuelled ships (if enabling infrastructure investments happen)	• air transport using pure biodiesel • air transport using hydrogen	• transition to pure hydrogen for heating

Note: BG refers to biogas, BM refers to biomethane, LNG refers to liquefied natural gas, CNG refers to compressed natural gas, LPG refers to liquefied petroleum gas, and HGV refers to heavy goods vehicle.

Source: Oxera analysis.

Box 6.1 summarises our findings in the transport sector for each of the technologies examined. We find that biogas/biomethane and biofuels can be particularly useful in decarbonising heavy goods vehicles (HGVs), ships and aeroplanes—i.e. those vehicles which are not suitable for electrification. The role of low-content biofuels in transport is often as a blend with existing fuels; therefor, this does not eliminate emissions, but serves as a transitional measure. In the medium to long term, biogas and hydrogen could play a role for heavy vehicles and hard-to-electrify sectors in transport. For either biogas or hydrogen, significant investments would have to be undertaken across the value chain for production, transport and use. In any case, we note that local biogas production is a 'no regrets' strategy, as parts of Jersey's transport could be fuelled with CNG irrespective of what will emerge as the global winner in terms of zero-carbon HGV fuels.

Box 6.1 Summary: viability of technologies in the transport sector

Biogas, biomethane and liquefied biomethane

- **Upstream**: local biomethane production technology is well established and possible on Jersey, but production will not be sufficient to satisfy demand. Remaining quantities need to be imported.
- **Midstream**: if available, LNG infrastructure can be used.
- **Downstream**: if available, LNG and CNG vehicles can be used.

Liquefied biofuels

- **Upstream**: local biodiesel and bioethanol production from waste products is feasible on Jersey, but production will not be sufficient to satisfy demand. Remaining quantities need to be imported.
- **Midstream**: biodiesel and low-bioethanol blends can be distributed via existing infrastructure. The use of high-content blends requires investment.
- **Downstream**: biodiesel and low-bioethanol blends can be used in existing cars, HGVs, ships and aeroplanes with appropriate engines. The use of high-content blends requires investment.

Hydrogen

- **Upstream**: green hydrogen production technologies are established, but large-scale deployment of green hydrogen has not been achieved. Large investments are needed to build infrastructure on Jersey.
- **Midstream**: hydrogen requires specific distribution networks; large investments needed.
- **Downstream**: hydrogen-compatible cars are feasible in the short term, and HGVs are feasible in the medium to long term.

Note: LNG refers to liquefied natural gas, CNG refers to compressed natural gas, and HGV refers to heavy goods vehicle.

Source: Oxera analysis.

Box 6.2 provides a summary of the available fuel alternatives for the heating sector. We find that using biogas and biomethane can be valuable ways to reduce emissions in the short to medium term if the appropriate infrastructure is available. On Jersey, which runs mainly on LPG and oil for heating, biodiesel seems to be the only near-term feasible solution that does not require major investments. Because most buildings will need to be retrofitted in the medium to long term in order to decarbonise heating, air source heat pumps are likely to be the preferred solution due their superior efficiency.

Box 6.2 Summary: viability of technologies in the heating sector

Biogas, biomethane and liquefied biomethane

- **Upstream**: local biomethane production is a well-established technology and possible on Jersey, but production will not be sufficient to satisfy demand. Remaining quantities need to be imported.
- **Midstream**: LPG infrastructure on Jersey is not compatible with biomethane—retrofitting is needed.
- **Downstream**: LPG and oil boilers are not compatible with biomethane—retrofitting is needed.

Liquefied biofuels

- **Upstream**: local biodiesel production from waste products is a well-established technology and feasible on Jersey, but production will not be sufficient to satisfy demand. Remaining quantities need to be imported.
- **Midstream**: biodiesel blends can be distributed with heating oil infrastructure.
- **Downstream**: biodiesel blends can be used in oil boilers.

Hydrogen

- **Upstream**: green hydrogen production technologies are well established, but need to be rolled out at a large scale. Large investments are needed to build infrastructure on Jersey.
- **Midstream**: LPG infrastructure on Jersey is not compatible with hydrogen; large investments are needed.
- **Downstream**: LPG and oil boilers are not compatible with hydrogen; large investments are needed.

Note: LPG refers to liquefied petroleum gas.

Source: Oxera analysis.

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