What role for electromethane and electroammonia technologies in European transport's low carbon future?

Addendum to What role for electrofuel technologies in European transport's low carbon future?

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Abstract

A previous study, *What role is there for electrofuel technologies in European transport's low carbon future?* (Malins, 2017), reviewed the status of various technologies for producing drop-in liquid electrofuels using renewable electricity. This addendum report expands on that earlier study by considering the production of electromethane and electroammonia fuels. As in the case of drop-in liquid electrofuels, the production costs of electromethane and electroammonia are expected to be significantly higher (at least double and perhaps several times higher) than current fossil fuel prices for the foreseeable future, unless electricity can be delivered to electrofuel facilities at very low prices. The technologies for methane and ammonia production from hydrogen are more mature than technologies for drop-in liquid fuel synthesis, and the fuel synthesis step is potentially more energy efficient than processes for liquid hydrocarbon synthesis. However, the large scale required for economically efficient ammonia synthesis may present a challenge for facilities aiming to produce entirely renewable ammonia. Electromethane production should be able to achieve overall energy efficiency of 40-60%, while electroammonia production should be able to achieve efficiencies in the 40-70% range.

Both pathways have the potential to be low greenhouse gas intensity provided zero-carbon renewable electricity is used for the electrolysis process. As with drop-in liquid fuels, the use of electricity with even a modest greenhouse gas intensity would quickly eliminate the climate benefits of the system.

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1. Introduction

In 2017, Cerulogy published a review of the status and potential of power-to-liquids electrofuel technologies in the EU, *What role is there for electrofuel technologies in European transport's low carbon future?* (Malins, 2017), with a focus on opportunities to produce drop-in alternative liquid fuels for aviation and road transport. While there is great appeal in the production of substitute liquid fuels able to be used in existing engines, there are also interesting opportunities to produce other molecules from power, for use in engines designed or customised for that purpose. In this addendum report, we provide a brief overview of two additional electrofuel pathways – power-to-methane ('electromethane') and power-to-ammonia ('electroammonia'). It is recommended that the reader should familiarise themselves with the original report before reading this addendum.

Methane gas, with the chemical formula CH_4, is the main component of natural gas. Electromethane is chemically identical to fossil methane and is therefore fully substitutable with natural gas in all uses. While these gaseous fuels are currently mainly used for heat and power, methane can also be compressed or liquefied for use in transport, where it is mainly considered as a potential fuel for shipping or heavy duty vehicles.

Ammonia, with chemical formula NH_3, is not commonly used as a fuel at present, but has the advantage of being a carbon-free molecule, so that no carbon dioxide is produced by its combustion or by cracking for use in fuel cells. The combustion properties of ammonia are less favourable for fuel use than those of natural gas or liquid hydrocarbon fuels, but It has recently been identified by some stakeholders as a potential alternative fuel and/or hydrogen carrier for shipping.

1.1. Electromethane

The production of methane from electricity relies on the Sabatier reaction, in which hydrogen and carbon dioxide are combined at high temperature in the presence of a catalyst (methanation) (Grond, Schulze, & Holstein, 2013). Chemical methanation is a well-established technology, with the first commercial scale coal to gas plant having opened in the United States in 1984[1]. Sabatier methanation is characterised by (Willquist, 2017) as having reached technology readiness level 7-8.

The thermochemical Sabatier methanation process is the main one considered in this report. While the chemical methanation process is well established, there are also possibilities for biological methanation, using enzymes instead of catalysts to allow lower process temperatures. A 1 MW demonstration facility for the biological power-to-methane technology opened in Denmark at the BIOFOS wastewater plant in 2016 (Electrochaea, 2017). Biological methanation is characterised by Willquist (2017) as having reached technology readiness level 6-7.

1.1.1. Electromethane for transport

Methane can be used as a transport fuel in converted or custom built engines, generally as

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1   https://www.netl.doe.gov/research/coal/energy-systems/gasification/gasifipedia/great-plains

an alternative to diesel. Ricardo-AEA (2016) identify economically viable opportunities for the use of LNG in shipping when the full costs of fuel use are assessed, partly due to the air quality benefits of LNG use compared to the use of conventional bunker fuels. The societal benefit could be increased by the use of low carbon methane, such as biomethane or renewable electromethane. For road transport, they find that the economic case is not convincing to switch to fossil methane, but that for low carbon methane there may also be an opportunity (assuming an external cost of 90 € per tonne for carbon dioxide equivalent emissions). The benefits are sensitive to the environmental performance of the methane used and to rates of methane slippage, which can potentially be high especially for LNG fuelled ships.
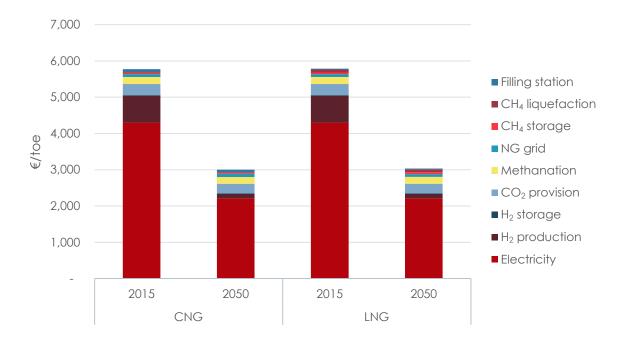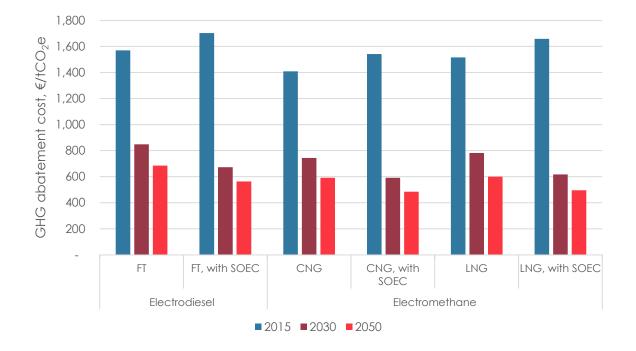

Figure 1.   Estimated production cost for electromethane with low temperature electrolysis, delivered as CNG or LNG (Schmidt et al., 2016)

Schmidt, Zittel, Weindorf, & Raksha (2016) provide estimates of fuel supply costs and carbon dioxide abatement costs for various electrofuel technologies given their assessment of fuel production costs and GHG performance. Figure 1 shows the estimated production costs for electromethane now and in 2050. Even with significant cost savings to 2050, the production costs are expected to exceed the current price of natural gas (currently about 300 €/toe to non-household consumers in the EU excluding taxes[2]) by about a factor of ten. As shown in Figure 2, they expect that the abatement cost for electromethane will be marginally below that for drop-in fuels. This cost advantage be somewhat offset however by the structural barriers to increasing supply of gaseous fuels for transport. The cost of infrastructure development for the large scale use of methane as a transport fuel are not included in these calculations, and are likely to be substantial. For each fuel type, a case is shown on the left of Figure 2 with low temperature electrolysis (currently available technology) and a case is shown on the

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2   http://ec.europa.eu/eurostat/statistics-explained/index.php?title=Natural_gas_price_statistics&oldid=290000

right with high temperature solid oxide electrolysis (SOEC) (a potentially more efficient future technology).

Figure 2. **Estimated carbon dioxide abatement cost for electrodiesel and electromethane pathways with and without SOEC electrolysis (Schmidt et al., 2016)**

1.2. Electroammonia

Ammonia is a molecule composed of one nitrogen and three hydrogen atoms (NH_3). The primary current use for ammonia is as a base molecule for fertiliser manufacture. Ammonia is manufactured in the Haber-Bosch process from hydrogen and air-captured nitrogen (N_2). At present, hydrogen is generally produced through steam reforming of natural gas. In future, however, hydrogen for ammonia synthesis could be produced through electrolysis instead. As with other electrofuels, if the electrolysis uses renewable electricity, electroammonia has the potential to have a low lifecycle greenhouse gas intensity.

While ammonia has traditionally been seen as a chemical building block rather than as an energy carrier, in the context of the move towards decarbonisation of the economy interest has been increasing in the potential to use ammonia as an energy storage medium, or directly as a transport fuel. Ammonia has particular appeal as an energy carrier for transport because it is more easily distributed than hydrogen, but because there is no carbon atom in an ammonia molecule it shares the property that it releases no carbon dioxide at the point of energy recovery (whether through combustion or in a fuel cell). In principle, using ammonia as a transport fuel would therefore allow the elimination of distributed carbon dioxide emissions (no

carbon dioxide would be emitted from the tailpipe/funnel of vehicles combusting ammonia or using it in fuel cells, but there might still be carbon dioxide released at processing facilities in the ammonia suppky chain). If carbon dioxide could be eliminated in the supply chain by deriving hydrogen from zero-carbon renewable electricity through electrolysis then the full ammonia lifecycle could be made carbon dioxide free.

The Haber-Bosch process for ammonia production is well established at commercial scale, with technology readiness level 9. Other ammonia synthesis technologies, however, remain at the research and development stage.

1.2.1. *Alternative ammonia synthesis technologies*

While the vast majority of global ammonia production takes advantage of the Haber-Bosch process, there are a range of alternative technologies that have been explored and that might in future allow reduction in cost, in energy consumption or in facility size for ammonia production.

One Haber-Bosch alternative is solid state ammonia synthesis (Insitute for Sustainable Process Technology, 2017; Lan, Irvine, & Tao, 2013). One major appeal of a solid state electrolytic process is the opportunity to produce ammonia at mild temperatures and pressures, avoiding the need for purification of N_2 and H_2 and reducing the necessary energy inputs compared to the energy intensive Haber-Bosch process. While the synthesis of ammonia from water and air using electricity in mild conditions has been demonstrated in the laboratory, the production rates achieved are currently at least an order of magnitude below what is considered necessary to make this process commercially viable (Institute for Sustainable Process Technology, 2017). Solid state synthesis technologies are therefore still firmly in the research and development stage. (Hughes et al., 2015) identify three further variations on electrolytic ammonia synthesis: liquid electrolytes; molten salts; and composite membranes.

Biochemical alternative technologies for ammonia synthesis include the use of cyanobacteria. For instance, Brouers, de Jong, Shi, Rao, & Hall (1987) describe the potential for photosynthetic ammonia production by the cyanobacterium *Anabaena azollae*. Similarly, Razon (2013) describes a process in which ammonium sulphate could be produced by the cyanobacterium *Anabaena* sp. ATCC 33047, and this in turn could be decomposed into ammonia and sulphuric acid. The production of ammonia photosynthetically has obvious appeal in terms of reduced consumption of non-renewable energy, but these technologies are also firmly at the research and demonstration phase, and are associated with the same challenges as algal biofuel production more generally.

It seems likely to be at least a decade before these alternative ammonia synthesis technologies achieve commercial scale (e.g. Siemens anticipate ammonia production through electrolysis being commercial in the 2030 timeframe, Hughes et al., 2015). Given the difficulty of obtaining data for these novel processes, they are not analysed in detail in this report. The only pathway analysed in detail is Haber-Bosch ammonia synthesis using hydrogen from electrolysis with renewable electricity.

1.2.2. *Electroammonia for transport*

Ammonia can in principle be used as a transport fuel either directly through combustion in

modified diesel engines, or in electric drivetrain vehicles through fuel cells. In particular, some stakeholders have identified ammonia as a potential shipping fuel.[3]

When used in a fuel cell, ammonia becomes essentially a hydrogen carrier. The ammonia (NH_3) must be catalytically decomposed into N_2 and H_2 (Vajo, 2003). The energy in the hydrogen can then be extracted from the fuel cell. Producing and then decomposing ammonia introduces significant inefficiencies into the system compared to utilising hydrogen directly. As noted below (cf. section 4.2), the energy conversion efficiency of the Haber-Bosch process is up to about 90% but could be rather lower in practice. The decomposition of ammonia is endothermic with a maximum theoretical energy conversion to hydrogen of 87%, but as the decomposition of ammonia is likely to require high temperatures the practical efficiency is likely to be more like 60-75% (Cheddie, 2016; Vajo, 2003). Using ammonia as a hydrogen carrier would therefore likely impose energy losses on the system of 35-50% compared to direct hydrogen use. These inefficiencies must be weighed against the less costly and difficult handling requirements of ammonia compared to hydrogen.

The potential for use of ammonia in fuel cells is limited by the limited deployment of fuel cell technology. Direct combustion of ammonia offers the possibility in principle of being more rapidly adopted. Ammonia has challenging combustion properties, but might be utilised in dual fuel engines as a natural gas alternative[4] or in custom designed engines. For instance, the Caterpillar Company patented an ammonia fuelled engine in 2008.[5] Certainly though adapting ships to burn ammonia would be more technically challenging than adapting them to use natural gas, for instance. Given the high nitrogen content in ammonia, there is a risk of high NOx emissions, but these emissions should be manageable with careful control of ammonia combustion conditions in the engine and appropriate after treatment technology.

Ammonia is toxic, and therefore the use of ammonia as a transport fuel would require the implementation of safe handling systems similar to those already in place in the fertiliser industry.

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3   E.g. https://c-job.com/ammonia-as-ships-fuel-c-jobs-future-proof-way-of-thinking/, http://www.ammoniaenergy.org/bunker-ammonia-carbon-free-liquid-fuel-for-ships/

4   https://www.technavio.com/report/global-tools-and-components-dual-fuel-engine-market

5   http://www.ammoniaenergy.org/ammonia-powered-internal-combustion-engines/

2. Economics

2.1. Electromethane

Electromethane production is included as a pathway in Brynolf, Taljegard, Grahn, & Hansson (2017). The methane synthesis process is expected to be less costly than more complicated processes for synthesising drop-in liquid fuels. Brynolf et al. (2017) report that current investment costs for catalytic and biological methanation are estimated in a variety of studies, with a range of 30-900 €/kW$_{fuel}$, depending on facility size. This is substantially below (but overlaps) the reported range given for Fischer-Tropsch (FT) liquid fuel synthesis (300 – 2100 €/kW$_{fuel}$). In their modelling, Brynolf et al. (2017) estimate a range of cost contribution from methanation investment to the price of the finished fuel from 10 to 110 €/toe. As one might expect given the simpler methane molecules being synthesised, methanation also has a higher conversion efficiency than the FT process (a reported range of 70-83% [LHV] for the fuel synthesis step, against 59-83% [LHV] for FT).
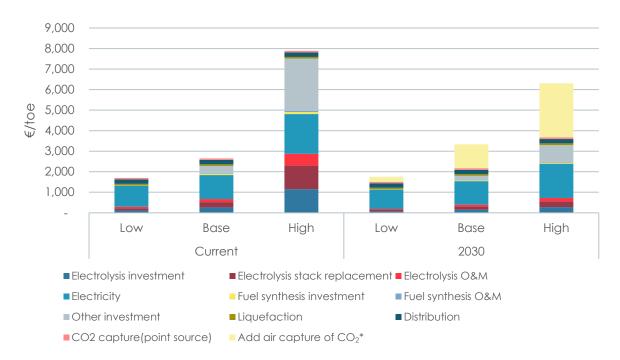

Figure 3. Division of costs for Sabatier electromethane pathway (current and 2030) (including liquefaction for supply as LNG)

Source: Brynolf et al. (2017). 'Current' modelled facility with: alkaline electrolyser; 5 €cent/kWh electricity; small scale; CO_2 from industrial point source; capacity factor 80%; 5% interest rate. '2030' modelled facility with: alkaline electrolyser; 5 €cent/kWh renewable electricity; medium scale; CO_2 from industrial point source; capacity factor 80%; 5% interest rate. Liquefaction and distribution costs taken from Schmidt, Zittel, Weindorf, & Raksha (2016).

*Additional cost of air capturing CO_2 shown for 2030 case, based on CO_2 capture costs of 138, 500 and 1000 €/tCO_2e for low, base and high scenarios respectively (cf. Brynolf et al. 2017).

Figure 3 presents cost estimates for electromethane production from Brynolf et al. (2017) for a 'current' technology case, and then assuming efficiency improvements and cost reductions by 2030. Even with access to a relatively low cost (5 €cent/kWh) supply of renewable electricity, production costs are likely to remain significantly above the pre-tax price of fossil fuel alternatives. The 'current' cost case assumes CO_2 capture from a relatively low cost industrial point source. For the 2030 cost case, the additional cost of adding air capture of CO_2 is also shown. There is considerable uncertainty regarding the long term cost of CO_2 air capture. Adding a CO_2 air-capture cost of 500 €/tCO_2e (as modelled in the air capture scenario in Brynolf et al. (2017) would increase methane production costs by about 1,000 €/toe.

An alternative to the Sabatier chemical methanation process would be methanation of hydrogen and carbon dioxide using biological agents. According to some sources, biological methanation may be able to be competitive with thermochemical catalytic methanation in the relatively near term. For instance, Grond et al. (2013) report capital cost estimates for biological methanation from the Fraunhofer Institute as low as 100 €/kW_{fuel}, for a large facility.

2.2. Electroammonia

The production of ammonia through the Haber-Bosch process requires high pressures (150 to 250 atmospheres) and temperatures (400-500 °C). Ammonia plants are large, capital intensive facilities built to achieve economies of scale. Maung, Ripplinger, Mckee, Saxowsky, & Station (2012) suggest a factor seven difference in investment costs per tonne of ammonia produced between a large (1.5 million tonne per year) and small (3,400 tonnes per year) ammonia plant. The average capacity of ammonia plants in Europe is just under 500 thousand tonnes per year, with a median size of 400 thousand tonnes (Egenhofer et al., 2015). The smallest plant in Europe has a 9 thousand tonne per year capacity.

Plant size may be a significant challenge for commercialising electroammonia production. A relatively large electrolysis facility (100 MW electricity input) operating for 8000 hours a year could support about 150 thousand tonnes per year of ammonia production, rather smaller than the current EU average facility size. Standalone electroammonia production may therefore struggle to achieve full economies of scale for current Haber-Bosch technology. One possibility for the short term might be to feed hydrogen from electrolysis as a complement to hydrogen from steam methane reforming at existing ammonia plants.

Figure 4 shows estimated current and future electroammonia costs for three cases, where the low reflects best case electrolysis costs and a large ammonia synthesis facility and the high case represents worst case electrolysis costs and a small ammonia synthesis facility.
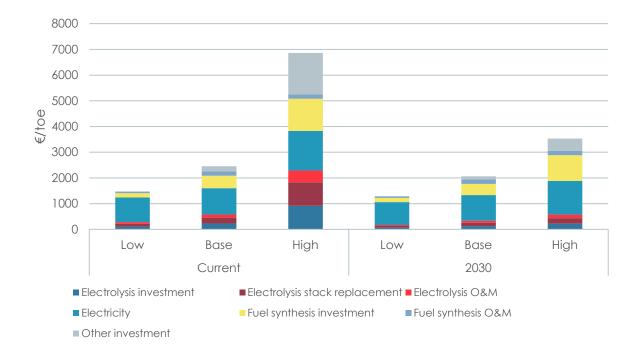
Figure 4.   **Division of costs for electroammonia pathway (current and 2030)**

Source: For electrolysis, Brynolf et al. (2017). 'Current' modelled facility with: alkaline electrolyser; 5 €cent/kWh electricity; small scale; CO_2 from industrial point source; capacity factor 80%; 5% interest rate. '2030' modelled facility with: alkaline electrolyser; 5 €cent/kWh electricity; medium scale; CO_2 from industrial point source; capacity factor 80%; 5% interest rate.

For Haber-Bosch ammonia synthesis, Maung et al. (2012). 'Low' cost case reflects a one million tonne per year ammonia synthesis facility, 'base' case a 50,000 tonne per year facility and 'high' a 3,400 tonne per year facility, assuming 5/10/20% by 2030 investment cost reduction for low/base/high cases respectively.

3. Lifecycle greenhouse gas implications

3.1. Electromethane

The lifecycle energy and greenhouse gas intensity of electromethane synthesis is similar to that for liquid electrofuel pathways, with the difference that electromethane synthesis is expected to be less energy intensive than FT fuel synthesis or than synthesis of drop-in fuels via methanol, and that distribution and use of methane is associated with a degree of methane leakage. Methane leakage is important to the lifecycle greenhouse gas intensity performance, as methane has a significantly higher global warming potential than carbon dioxide, and therefore even modest rates of leakage can undermine the climate performance of the overall fuel pathway.

Figure 5 shows a set of scenarios for greenhouse gas intensity for electromethane depending on whether it is supplied as LNG for ships or as CNG or LNG for road transport, on whether the power for the methanation process is renewable and on the level of methane leakage. Process data is based on the JEC Well-to-Wheels study (Edwards et al., 2013), while the low, medium and high scenarios for methane leakage rates are based on work by the International Council on Clean Transportation (Delgado & Muncrief, 2015; Lowell, Wang, & Lutsey, 2013) (Table 1). These methane leakage rates are significantly higher than those included in the JEC work, and include estimated operational leakage in addition to leakage in the supply chain. Zero leakage has been assumed at the methanation facility itself.

Table 1.   Rates of methane leakage assumed in fuel distribution and use

	Low	Medium	High
CNG for road	0.4%	0.8%	2.0%
LNG for ships	0.50%	1.50%	3.40%

All of the GHG intensity cases illustrated in Figure 5 assume that zero-carbon renewable electricity is used for electrolysis. As discussed in Malins (2017), the GHG performance for electrofuels would be severely undermined if the power utilised is not zero carbon. This is discussed further below in section 4.3. The JEC assumptions for energy expenditures in the production process are shown in Table 2.
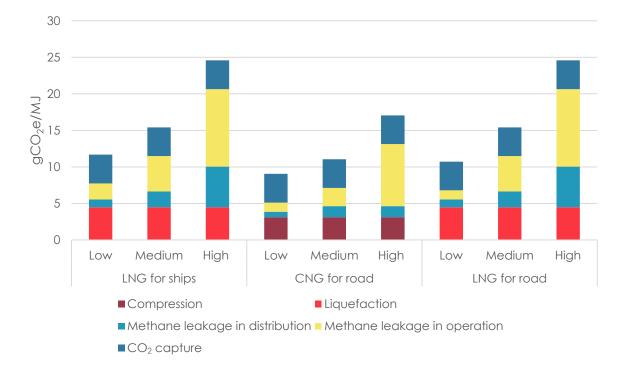
Figure 5.   Cases for greenhouse gas intensity of electromethane with different leakage rates

Assumes zero carbon renewable power for electrolysis and grid electricity for compression and liquefaction, and CO_2 capture. Grid electricity assumed to have a greenhouse gas intensity of 141 gCO_2e/MJ (Edwards et al., 2013). Excess heat from methanation is assumed to be utilised in carbon absorption.

The results shown in Figure 5 and Table 2 are based on the case considered by the JEC, and assume absorption of CO_2 from an industrial point source. Adding air capture of CO_2 could significantly increase energy requirements for the system. The minimum energy requirement for capture of CO_2 from the air has been estimated at 400 kJ/mol CO_2e (House et al., 2011). This implies an additional power requirement of about 0.5 MJ per MJ of methane output. If energy for air capture of CO_2 was supplied from current grid electricity, this would add 70 gCO_2e/MJ to the greenhouse gas intensity of the process, almost eliminating any CO_2 emissions reduction compared to fossil fuels. From a greenhouse gas reduction point of view, if capturing CO_2 from the air it would therefore be almost as important to ensure that electricity for CO_2 capture is low (or ideally zero) carbon as to ensure that electricity for electrolysis is zero (or near-zero) carbon.

Table 2.   Energy consumption in electromethane production and distribution, MJ per MJ of produced methane (Edwards et al., 2013)

	MJ/MJ
Electrolysis	1.85
Electricity for CO_2 absorption (point source)	0.002
CO_2 compression	0.01
Heat for CO_2 absorption (point source)	0.24
Excess heat from Sabatier reaction	-0.20
Net heat requirement	0.04
Compression and dispensing (CNG case)	0.07
Liquefaction and dispensing (LNG case)	0.10
Additional energy for air capture of CO_2	0.5
Overall energy requirement (value with air capture of CO_2 in brackets)	*2.1 (2.6)*
Overall energy efficiency (value with air capture of CO_2 in brackets)	*49% (39%)*

3.2.   Electroammonia

The process of ammonia production via Haber-Bosch has a reputation for high energy use. Haas & Dijk (2010) report an average net energy consumption for ammonia synthesis in Europe of 34.7 GJ/tonne, including the energy in the natural gas being reformed for hydrogen production. As ammonia has a lower heating value of 18.6 GJ/tonne, this gives the ammonia synthesis process a 54% energy efficiency including steam methane reforming. The GREET model (Argonne National Laboratory, 2017) reports a slightly lower energy efficiency for the ammonia production process (based on U.S. data) with 39 GJ/tonne of energy inputs. In electroammonia production, hydrogen from electrolysis replaces the energy intensive steam methane reforming step, but ammonia synthesis may still require significant energy inputs. It is therefore necessary to disaggregate the energy requirements of ammonia synthesis from the energy requirements of steam methane reforming.

Bañares-Alcántara et al. (2014) report power consumption for Haber-Bosch ammonia synthesis of 2.2 – 14.4 GJ/tonne, depending on loading (the plant is assumed to run with higher efficiency when it has a 100% load factor, and much less efficiently for a 10% load factor). They suggest therefore that it would be important to seek to maximise utilisation of the ammonia synthesis unit in order to avoid large efficiency losses. For electrolysis efficiency of 65%[6], this range of power consumption would give an efficiency range for ammonia synthesis of 90% at high load

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6   Achievable in the near term for low temperature electrolysis.

to 56% at low load, and for the full system of 58% at high load to 37% for low load, ignoring heat generated by the exothermic ammonia synthesis reaction. Utilising by-product heat (for instance for high temperature electrolysis) would allow a higher overall system efficiency. Maung et al. (2012) suggest that energy efficiency may be affected by plant size as well as loading, identifying nearly a factor ten difference in electricity cost per tonne of production between a smaller (50 thousand tonne) and larger (500 thousand tonne) ammonia synthesis facility.
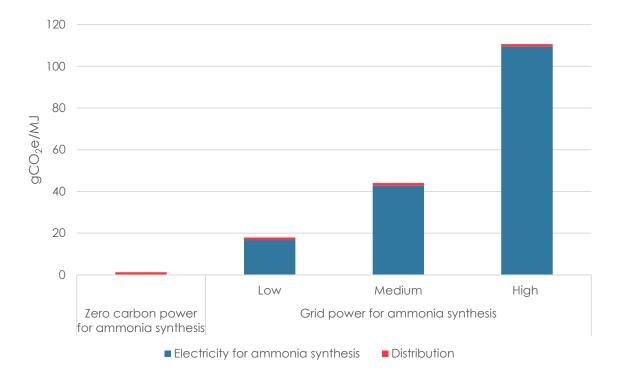
Institute for Sustainable Process Technology (2017) report overall system efficiencies for power-to-ammonia pathways ranging from 47% (for high temperature solid state synthesis) to 73% (for SOEC electrolysis), which is consistent with an assumed energy conversion efficiency from hydrogen to ammonia of about 90%. This study finds that even given heat transfer from the synthesis step, the high temperature electrolysis option (SOEC) would require additional heat inputs equal to 4% of total power input. Bañares-Alcántara et al. (2014) report energy inputs and exergetic efficiencies for a variety of technology combinations for electrolysis, nitrogen extraction and ammonia synthesis. The overall ammonia production efficiency reported ranges from 50% to 59%. Details of two technology pathways are given in Table 3.

Table 3.   Energy consumption in electroammonia production, MJ per MJ produced ammonia

	Alkaline electrolysis (atmospheric pressure)		PEM electrolysis	
	Energy requirement	Exergetic efficiency	Energy requirement	Exergetic efficiency
Electrolysis	2.03	55%	1.79	65%
Nitrogen separation	0.02		0.02	
Ammonia synthesis	0.10	88%	0.04	90%
Overall	*2.15*	*51%*	*1.85*	*59%*

Nitrogen extraction by cryogenic separation, ammonia synthesis with Fe catalyst, data from Bañares-Alcántara et al. (2014).

Figure 6 illustrates several cases for the greenhouse gas intensity of electroammonia fuel production using zero carbon renewable electricity for the electrolysis step. The greenhouse gas intensity for the use of grid electricity for electrolysis is discussed in section 4.3. On the left bar of Figure 6, the case is shown in which all power for hydrogen electrolysis and ammonia synthesis comes from zero carbon renewables. In this case, the GHG intensity is near zero for the pathway. On the three bars to the right, three levels of emissions are illustrated for the use of grid electricity in the ammonia synthesis step based on power demand reported by Bañares-Alcántara et al. (2014), from low (assuming 2.2 GJ/tonne power requirement) to high (assuming 14.4 GJ/tonne power requirement). For the most efficient ammonia synthesis case, the lifecycle emissions remain low. However, for the least efficient ammonia synthesis process the use of grid electricity could potentially eliminate greenhouse gas benefits compared to conventional fossil fuels, even when using zero carbon renewable electricity for the electrolysis

step. This underlines the importance of developing any electroammonia production at a scale and utilisation rate that allows for efficient production.

Figure 6.   Cases for greenhouse gas intensity of electroammonia

Low, medium and high cases reflect range of power consumption for ammonia synthesis step as reported for different loads by Bañares-Alcántara et al. (2014). Distribution emissions assumed to be the same as for synthetic liquid hydro-carbon fuels.

3.3.   Sensitivity to electricity inputs

Above it was noted that for a low-efficiency ammonia synthesis process, the use of grid electricity could significantly undermine greenhouse gas intensity performance, even with zero carbon electricity for electrolysis. Further to this, as documented by Malins (2017), the environmental performance of electrofuel technologies in general is highly dependent on the environmental performance of the input power used for the electrolysis. Given overall conversion efficiencies from electricity to fuel of the order of 50%, if the input electricity is not zero carbon, the environmental benefits of electrofuel production are rapidly reduced. Figure 7 and Figure 8 show the impact on the lifecycle greenhouse gas intensity of ammonia production of using higher GHG intensity electricity sources for hydrogen production by electrolysis as well as the ammonia synthesis stages. Even for a relatively low GHG intensity electricity supply (e.g. electricity from woodchips with an assumed carbon intensity of 49 gCO_2e/MJ, a third of the grid average) the climate benefit of the fuels considered is largely eliminated.
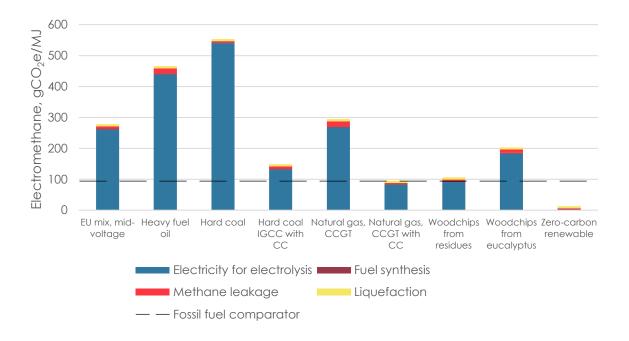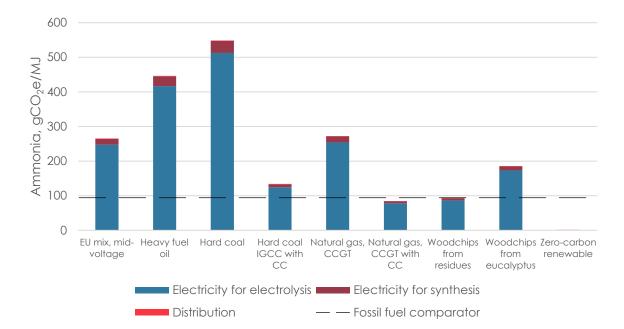
Figure 7.   GHG intensity of electromethane for varying electricity sources

Case of LNG for road transport with medium methane leakage

Figure 8.   GHG intensity of electroammonia with varying electricity sources for electrolysis

4. Discussion

In this addendum report, which accompanies the report *What role is there for electrofuel technologies in European transport's low carbon future?* (Malins, 2017), we have reviewed potential costs and greenhouse gas emissions implications of the production of electromethane and electroammonia using hydrogen from electrolysis with renewable energy. The estimated production costs for both of these fuels are significantly higher than current pre-tax prices for fossil fuel alternatives. The EU weekly oil bulletin of 5/3/2018[7] reported the average consumer price of road diesel at 550 €/toe and the average price of low sulphur (<1%) fuel oil at 405 €/toe, while Argus reported the delivered LNG price for Northwest Europe at around 270 €/toe in August 2015 (Argus, 2015). Both the expected costs and potential benefits are somewhat comparable to the costs and benefits estimated for drop-in liquid electrofuels (see Figure 9), but with some important caveats.
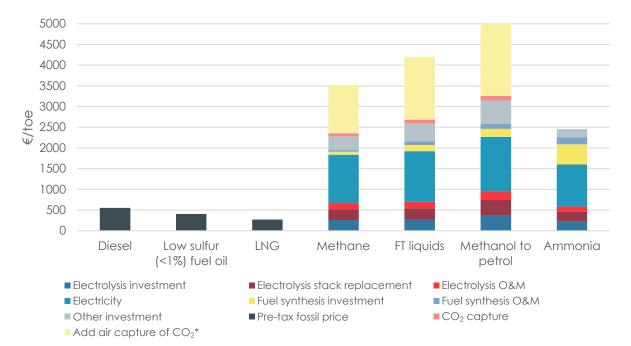

Figure 9.   Comparison of estimated base-case near term production costs for various electrofuels

Additional cost to replace CO_2 capture from point source with CO_2 air-capture cost of 500 €/tCO_2e.

See above and Malins (2017) for discussion of cost assumptions.

Firstly, due to the simpler chemistry required, electromethane production is likely to be more energy efficient and less costly than production of electrodiesel. On the other hand, there is the risk of methane slip in the gas supply chain and during operations, which can undermine the climate benefits due to the high global warming potential of methane. Nevertheless,

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7   https://ec.europa.eu/energy/en/data-analysis/weekly-oil-bulletin

even for a relatively high methane leakage scenario for electromethane supplied to ships as LNG, provided zero carbon electricity is used for the electrolysis a significant climate benefit is possible compared to a diesel or bunker fuel comparator. It is also important to remember that electromethane has no potential as an aviation fuel.

Secondly, the cost profile of ammonia synthesis benefits from avoiding the need for CO_2 capture, but suffers from the relatively high investment costs anticipated for the Haber-Bosch ammonia synthesis process.

Thirdly, both the economic and environmental performance of ammonia production benefit from scale. Even a large electrolysis facility would be able to support only a relatively small ammonia synthesis plant, which may impact GHG performance and raise capital costs. Successful commercialisation of distributed electrolytic ammonia production is likely to require resolving these efficiency issues. It may also be assisted by novel ammonia synthesis technologies, such as solid state electrolytic synthesis or biochemical synthesis.
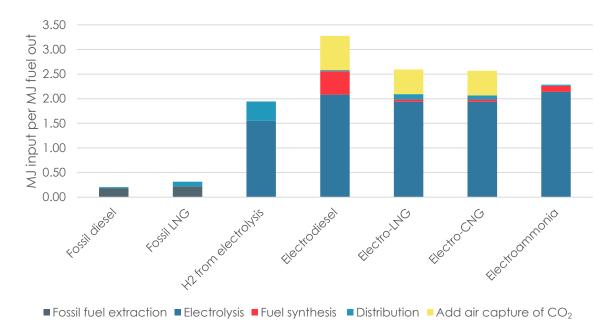

Figure 10. Comparison of energy inputs to different fossil and electrofuel systems

Ammonia energy inputs based on Bañares-Alcántara et al. (2014), energy requirement for air capture of CO_2 assumed to be 400 kJ/mol, all other energy inputs taken from Edwards et al. (2013). Chemical energy in crude oil/natural gas not included in characterisation. Figure includes losses in electricity transmission based on Edwards et al. (2013).

Any electrofuel pathway involves some level of compromise between overall energy efficiency and the convenience and utility of the output fuel product. Figure 10 provides a comparison of potential energy expenditures in the supply chains of various electrofuels, compared to energy expenditures in the fossil fuel supply chain (Bañares-Alcántara et al., 2014; Edwards et al., 2013). As noted in Malins (2017), the overall efficiency of systems taking renewable electricity, converting it into an electrofuel and using that fuel in a combustion engine, or even fuel cell, will always fall well short of the efficiency of using electricity for electric drive vehicles.

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