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Keywords Carbon-neutral synthetic fuels, electrofuels, advanced biofuels, battery electric vehicles, low-carbon transportation alternatives

JEL Classification Q41, Q42, Q55, R41, R48, O33

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The race to solve the sustainable transport problem via carbon-neutral synthetic fuels and battery electric vehicles

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Abstract

Carbon-neutral synthetic fuels (CNSFs) could offer sustainable alternatives to petroleum distillates that currently dominate the transportation sector, and address the challenge of decarbonising the fuel mix. CNSFs can be divided into synthetic biofuels and 'electrofuels' produced from CO_2 and water with electricity. We provide a framework for comparing CNSFs to battery electric vehicles (BEVs) as alternatives to reduce vehicle emissions. Currently, all three options are significantly more expensive than conventional vehicles using fossil fuels, and would require carbon prices in excess of \$250/tCO_2 or oil prices in excess of \$150/bbl to become competitive. BEVs are emerging as a competitive option for short distances, but their competitiveness quickly deteriorates at higher ranges where synthetic biofuels are a lower-cost option. For electrofuels to be viable, the challenge is not simply technological learning, but access to a low-cost ultra-low-carbon electric power system, or to low-carbon electric generators with high annual availability.

Introduction

Energy demand in transport has grown faster than in most other sectors, globally more than doubling from 45 EJ in 1973 to 110 EJ in 2014 and increasing its share of total final consumption from 23% to 28% (IEA, 2016). Driven by rapid growth in demand, CO_2 emissions also more than doubled over this period with little change in the fuel mix – petroleum products accounted for 96% of transportation sector energy consumption in 2012 (EIA, 2016a).

Despite robust historical emissions growth, changes in vehicle technology and fuels and pressures for climate action may portend a very different future. The 2015 Paris Accord establishes a target of restraining global temperatures to 2°C, which would require aggressive action to reduce overall demand for transport, coupled with ambitious decarbonisation of the remaining demand. Under the International Energy Agency (IEA) baseline projection, global transport demand would increase to 160 EJ by 2050. To be consistent with Paris Accord targets, however, demand would need to be constrained to 102 EJ, or roughly current levels, but would need to be substantially less carbon-intensive (IEA, 2017a). As a shorthand, shifting towards low-carbon transport can be seen as solving the '100 EJ Problem'.

Deep reductions in emissions can be accomplished by decarbonising fuels, or vehicle technologies, or a combination of both. Options to reduce fuel carbon intensity include: (i) shifting from petroleum to natural gas, (ii) switching from fossil fuels to biofuels, and (iii) producing so-called 'electrofuels' or CCU (carbon-capture and utilisation) fuels using CO_2, water and low-carbon electricity. Natural gas vehicles are now relatively common as fleet vehicles, but offer minor reductions in carbon intensity (JEC, 2014a). Current biofuel production is almost entirely corn or sugarcane ethanol or biodiesel from vegetable oils (IEA, 2017b). Despite strong support from agricultural interest groups, these first-generation fuels have come up against availability constraints, sustainability concerns, public opposition and basic economics (Mohr and Raman, 2013). Instead, attention has shifted to advanced biofuels derived from non-edible lignocellulosic residues and wastes, because of their potential to offer significant volumes of low-GHG hydrocarbon fuels at scale while avoiding many concerns associated with first-generation biofuels.

We focus on synthetic hydrocarbons, produced from lignocellulosic feedstocks via gasification or from carbon dioxide and water via electrolysis, since they are two major options for decarbonising transport fuels that have received some attention in their own right, but are rarely examined in a comparative study. Synthetic hydrocarbon fuels can be used as perfect substitutes or "drop-in" fuel replacements that can be distributed and used at any blend ratios (unlike, say, first generation biofuels), thus enabling a gradual transition to alternative fuels without distribution- or vehicle-related barriers. Rather than focusing exclusively on fuels though, we offer a comparison with alternative powertrain technologies to highlight the different ways these options could contribute towards decarbonising ~100 EJ/yr transport energy demand in 2050.

Carbon-neutral synthetic fuels

Producing synthetic fuels from carbon and hydrogen is hardly novel. First introduced on an industrial scale in the 1920s, current technologies allow manufacturing of all products presently obtained from crude oil or natural gas from alternative feedstocks. Coal was used as a feedstock by both Germany during World War II and South Africa under Apartheid to derive liquid fuels when global petroleum markets were inaccessible. Natural gas has now largely replaced coal, owing to higher hydrogen content, better efficiency and fewer impurities.

Switching from fossil feedstocks to biomass is frequently proposed for decarbonising synfuel production, and its technical viability has been proven on a few occasions – the largest demonstration plant producing 20 MW of synthetic biomethane from 30 MW of lignocellulosic biomass (Alamia et al., 2017). In addition to transportation fuel, heat and electricity can be generated as co-products, driving the overall thermal efficiency up to 80 % (LHV) (Liu et al., 2011; Hannula, 2015). Also, if the by-product CO_2 from biomass processing is captured and securely stored in geological media, CNSFs would be characterised by strong negative net GHG emissions because of the storage of photosynthetic CO_2 (Liu et al., 2011; Sanchez and Kammen, 2016). Despite the technology's many virtues, most commercial-scale projects are currently on hold due to prohibitive high investment cost of pioneer process plants combined with a lack of sufficiently strong policies to incentivise their economics and share the risk of scale-up.

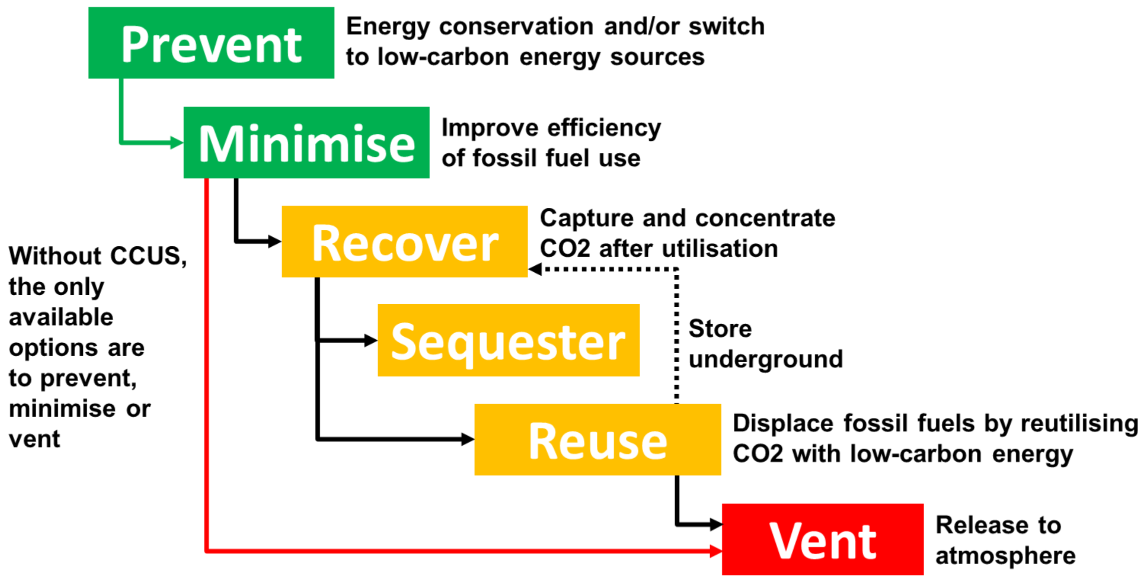

Figure 1. CCUS hierarchy. Illustration of the relationship between more traditional mitigation options (energy conservation, energy efficiency and low-carbon technologies like renewables and nuclear power) against the various options available under Carbon Capture Utilisation and Storage (CCUS). Once CO_2 is captured, options exist to either store it underground (CCS) or to reuse for a range of activities from fuels (electrofuels) to chemical production to enhanced hydrocarbon or commodity recovery. The worst environmental outcome is also the cheapest, namely venting to atmosphere.

Another option for decarbonised synfuels is the potential of converting CO_2 to fuels with low-carbon energy (Steinberg, 1978; Agrawal et al., 2007; Zeman and Keith, 2008; Jiang et al., 2010; Hannula, 2015). Interest in such electrofuels is motivated partly by reductions in the generation costs of wind and solar electricity, and by the increased penetration of these variable sources in the energy mix, which has led to low or even negative power prices (e.g. in Germany), and created demand for balancing services (Blanco and Faaij, 2017). Interest in electrofuels is also tied to the potential for using large volumes of carbon dioxide. In many countries, discussions have largely shifted from carbon capture and storage (CCS) to carbon capture utilisation and storage (CCUS), but implications of such a shift are only slowly being debated (Bruhn et al., 2016; Gale, 2017) and the potential scale of utilisation has been questioned (Mac Dowell et al., 2017). In Figure 1, we use the analogy of the traditional waste hierarchy of 'reduce, reuse, recycle' (Wolf, 1988) to illustrate the relationship of venting CO_2 to storing, reducing, or using CO_2 by converting to fuels. The potential for CCUS opens up many more pathways for action although historically it has been applied primarily to the power sector. Electrofuels are significantly more expensive than CCS for carbon management (Abanades et al., 2017), but they do not currently face similar political barriers as underground storage of CO_2, which has seen repeated setbacks in the past decade (Reiner, 2016). However, conversion of CO_2 to fuels does not automatically guarantee emissions savings, but needs to be combined with an ultra-low-carbon energy source to drive the conversion process (Koponen and Hannula, 2017).

The technical viability of CNSFs from CO_2 has been proven on a few occasions - the largest demonstration plant produces 3.2 MW (LHV) of synthetic methane from 6 MWe electricity (Otten, 2014). An online European database currently lists 76 projects (as of December 2017), of which about half (37) are situated in Germany. Most projects are hydrogen only, but 13 projects also feature chemical utilisation of carbon dioxide (CCU) to produce fuels. (European Power to Gas Platform, 2017). Whether fossil CO_2 could be used for electrofuels alongside biogenic and atmospheric CO_2 is currently being debated, but life-cycle assessment methodologies are only just being established. One potential resolution could be to integrate electrofuels and biofuels manufacture into a single process where by-product CO_2 from biomass processing is converted to additional fuel with electrolytic hydrogen (Hannula, 2016).

CNSFs are not the only route to sustainable hydrocarbon fuels. Hydrogenated vegetable oils (HVOs) are already commercial today at a scale of millions of tonnes per year, but their growth potential is limited by the availability of sustainable feedstocks. Production of pyrolysis oils from biomass followed by upgrading (Oasmaa et al., 2010; Elliott, 2007; Gueudré et al., 2017) in refineries is currently at early stages of experimentation, but could produce a sizable volume of advanced biofuels if the technology is successfully commercialised. Algae technology is currently at an early demonstration scale, but may enter the market post 2025 (EC, 2017).

Estimating the cost of CNSFs

The prospective costs of synthetic fuels have been extensively investigated in a series of "scoping" studies intended to inform public policy discussions on the use of synfuels to minimise environmental impacts. However, results from these past studies are very heterogeneous and a wide range of values have been proposed (Haarlemmer et al., 2014; Brynolf et al. 2017). Scoping studies typically evaluate costs at some future date based on mature technology. Such Nth-of-a-kind (NOAK) cost estimates are valuable for outlining the prospective long-term cost potential of CNSF, but are less useful in assessing costs of first-of-a-kind (FOAK) plants, as conventional cost estimation methods have routinely been found to understate the costs of pioneering FOAK technologies (Merrow et al., 1981; Ansar, 2014).

Table 1. Comparison of breakeven oil prices (BEOP, \$/bbl), GHG balances and abatement costs of alternative CNSF configurations. Cost estimates based on demonstration plant data and developed for first-of-a-kind plants that produce liquid hydrocarbon fuels at 160 MW (~2500 barrels per day) scale. Zero carbon price (\$/tCO2) assumed. Details of calculations and assumptions are presented in Supplementary Materials (Note 1).

CNSF plant configuration	Capacity factor	Energy cost[a] \$/MWh	BEOP[b] \$/bbl	Electricity gCO2/kWh	End-product gCO2/MJ	Relative emissions[c]	Abatement cost, \$/tCO2[d]	Carbon tax, \$/l
Synthetic biofuels[e]	85%	8 – 24	138 – 176		5	7 %	235– 338	0.6 – 0.9
Generator connected electrofuels[f]								
Nuclear	90%	112 – 183	392 – 606	3.7	3	3 %	885 – 1436	2.2 – 3.6
Geothermal	85 – 90%	77 – 117	287 – 407	6	4	5 %	626 – 944	1.6 – 2.4
Solar Thermal Tower + Storage	43% – 52%	98 – 181	391 – 641	8.8	6	8 %	926 – 1603	2.3 – 4.0
Solar PV - Utility scale								
Crystalline	21 – 30%	46 – 53	305 – 326	18	13	16 %	763 – 825	1.9 – 2.1
Thin film	23 – 32%	43 – 48	286 – 301	18	13	16 %	704 – 749	1.8 – 1.9
Wind								
Onshore	38 – 55%	30 – 60	181 – 271	7	5	6 %	350 – 591	0.9 – 1.5
Offshore	40 – 50%	71 – 155	314 – 566	8	6	7 %	710 – 1390	1.8 – 3.5
Grid connected electrofuels[g]								
EU-28	90%	114	398	447	310	410 %	No abatement	-
Germany	90%	149	504	615	427	564%	No abatement	-
France	90%	89	323	105	73	96%	17695	41.8
Sweden	90%	66	254	47	33	43%	894	2.1
Norway	90%	81	299	9	6	8 %	678	1.6

Notes:

a) *Cost is for energy inputs (biomass residues for advanced biofuel plant, electricity for electrofuel plant). Delivered cost of biomass feedstock \$40 - \$120/dry ton (assuming 19 MJ/kg lower heating value) from US DOE 2016 Billion-ton report figure ES.8, cost of electricity for different energy sources from Lazard's Levelized cost of energy analysis – version 11.0 (2017). Grid costs from Eurostat data for industrial consumers in 2016 including taxes and levies but excluding VAT.*

b) *Break-Even Oil Price. Assumptions used for all plants: 160 MW (LHV) liquid hydrocarbon output, wholesale fuel price multiplier 1.22, 20 yr economic life, 8% Weighted Average Cost of Capital (WACC). For an electrofuel plant producing liquid hydrocarbons, we assume: 40 % (LHV) fuel efficiency, \$479M total capital investment (TCI), annual operating and maintenance cost 2 % of TCI. For a biofuel plant producing liquid hydrocarbons, we assume: 50 % (LHV) fuel efficiency, \$828M total capital investment (TCI), annual operating and maintenance cost 4 % of TCI.*

c) *Lifecycle GHG emissions associated with the facility divided by lifecycle emission of fossil-derived product displaced. Carbon content of liquid hydrocarbons: 2.52 $kgCO_2/L$.*

d) *Based on \$50/bbl crude oil price.*

e) *End-product GHG emissions for synthetic biofuels (average based on farmed wood and waste wood) from JEC (2014b).*

f) *Minimum lifecycle emissions (incl. albedo effect) for selected electricity supply technologies from IPCC (2014a) Annex III: Technology-specific cost and performance parameters, Table A.III2.*

g) *Carbon intensities of electricity consumed in the low voltage portion of the electricity network including upstream emissions in 2015 from Moro and Lonza (2017).*

In recent years, however, a small amount of actual data on demonstration projects has surfaced, allowing indicative cost and performance estimates to be created for CNSFs from empirical evidence. We present our FOAK estimates for different CNSF alternatives at commercial scale in Table 1. Depending on feedstock cost, the breakeven oil price (BEOP) for biomass-based CNSF ranges from \$138 to \$176/bbl and the abatement cost from \$235 to \$338/tCO_2 (assuming \$50/bbl crude oil price). For grid-connected CNSF, the BEOP estimate ranges between \$254 – \$504/bbl, for selected countries. However, assuming current EU-average grid emissions of 447 gCO_2/kWh (Moro and Lonza, 2017), the produced fuel would exceed the emissions of petroleum fuels by about a factor of three. Even for 100 gCO_2/kWh grid intensity, emissions from electrofuels are still comparable to fossil fuels, so ultra-low carbon intensities (~50 g CO_2/kWh or less, like those available currently in Sweden, Norway, or Quebec), are required. An obvious way to circumvent the problem of high-carbon electricity grid is to connect CNSF plants directly to a low-carbon electricity source. However, this ties fuel production to the capacity factor of the power source, leading to higher costs. The BEOP estimate is \$286–\$301/bbl (\$704-\$749/tCO_2) for solar PV and \$181 – \$271/bbl (\$350 – \$591/tCO_2) for onshore wind. Thus, electrofuels produced with wind have lower average costs than with solar as a result of wind's higher capacity factor despite its higher LCOE. Current cost estimates for CNSFs are high across the board, but transport taxation is already high, for context, the *minimum* excise duty rates in the EU are currently set at 35.9 c/L for unleaded petrol, which converts to an effective carbon tax of €152/bbl (EC, 2003).

CNSFs vs alternative powertrains

It is useful to line up CNSF options side-by-side with electric vehicles to understand the relationship between different decarbonisation pathways. The first challenge of comparing decarbonised fuel with decarbonised vehicle technologies is being able to offer a fair comparison of options that provide similar utility to consumers. For example, a major concern for BEVs is extending the range both to offer a fair comparison and to deal with long charging times and so-called 'range anxiety' among consumers (Franke & Krems, 2013). Of course, longer ranges imply significant increases in battery size and hence vehicle cost.

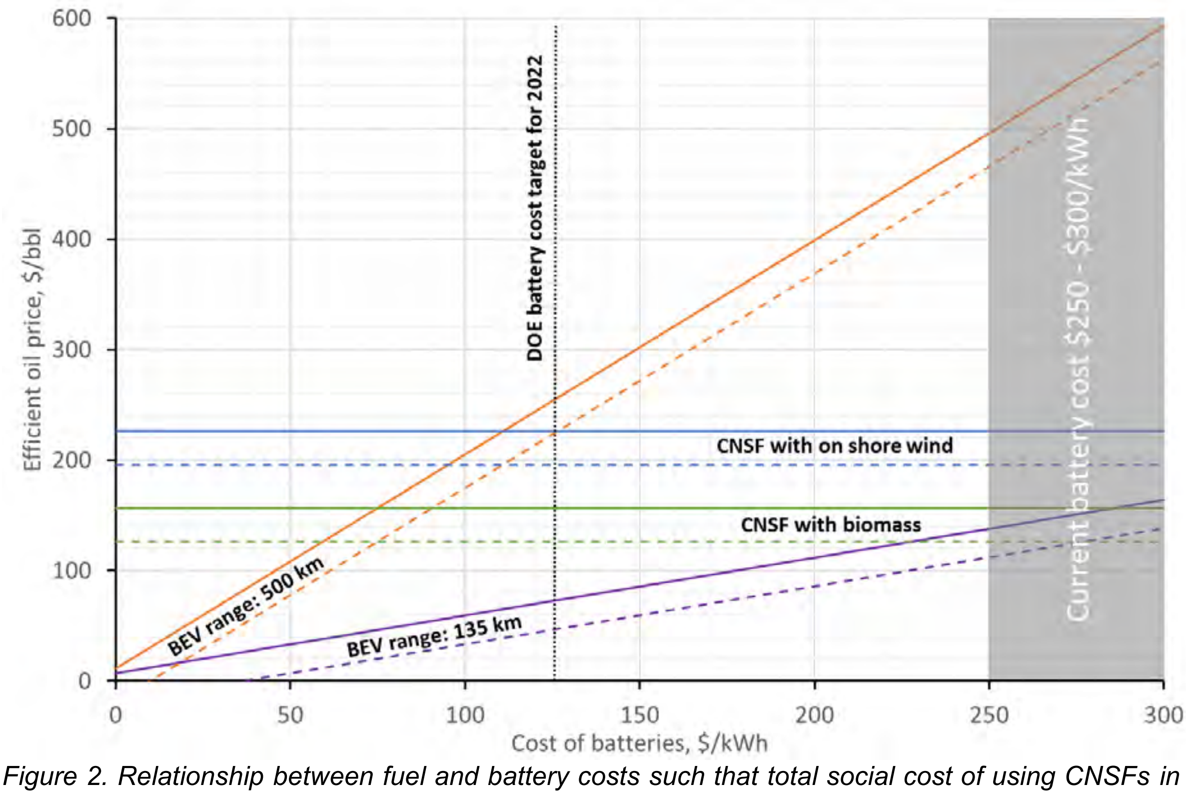

Figure 2. Relationship between fuel and battery costs such that total social cost of using CNSFs in a gasoline vehicle equals the total social cost of owning and operating an electric vehicle. Solid lines reflect a zero carbon price and dashed lines assume a carbon price of \$100/tCO2. Horizontal lines represent average break-even oil price estimates for selected first-of-a-kind CNSF technologies. Assumptions are presented in Supplementary Materials (Note 2). BEV results based on Newbery & Strbac (2016). Figure modeled on Covert et al. (2016).

Figure 2 illustrates the competition between internal combustion vehicles (ICVs) using gasoline and BEVs by plotting equal-cost curves across a battery cost range of \$0 to \$300/kWh. Separate curves are calculated for two different BEV ranges of 135 km (equivalent to the 2016 Nissan Leaf) and 500 km (long-range version of Tesla Model 3), which represent the bookends of currently available ranges for BEVs intended for the mass market. Assuming today's battery cost range of \$250 - \$300/kWh (Nykvist and Nilsson, 2015) and no carbon price, the equal-cost oil price is \$138-\$164/bbl for a 135-km range BEV and \$496-\$593/bbl for a 500 km BEV. Assuming the US Department of Energy (DOE) target cost of \$125/kWh for batteries in 2022 (USDOE, 2013) and no carbon price, the equal-cost oil prices are \$72/bbl and \$253/bbl for the 135 km and 500 km BEVs, respectively. The figure highlights the strong relationship between range and battery cost. At today's battery costs, all gasoline-substitutes that can be sustainably produced under about \$500 BEOP are competitive against a long-range BEV as a decarbonisation strategy, and achieving DOE's 2022 target of \$125/kWh, would still not outcompete CNSFs, including those made with electricity. On the other hand, short range BEVs are already competitive with CNSFs and present a tough challenge for any carbon-neutral fuels if the DOE target is reached. As Needell et al. (2016) show, lower-range vehicles such as the Nissan Leaf already would meet 87% of vehicle-days in the United States. However, the current low crude oil price in the range of \$40-\$60/bbl will obviously make any alternative fuel or drivetrain exceptionally challenging, without the sort of high subsidies currently being offered for BEVs, and even a \$100/tCO_2 price on carbon emissions (dashed lines) would have relatively little impact on the overall situation. Subsidies has been shown to be a significant predictor of market penetration (Sierzchula et al,. 2014). Although vital and generous in many countries, subsidies are also precarious. In Norway, for example, there are ten distinct forms of support for battery electric vehicles (Figenbaum et al., 2015). BEV uptake has proven very sensitive to subsidy levels, and may be difficult to sustain for rapidly rising overall support, as seen recently in the case of Hong Kong's subsidy removal when new BEV registrations dropped to zero (Yoo, 2017).

Figure 3 outlines the scale of the "100 EJ problem" by illustrating alternative supply scenarios, and the link between power sector emissions intensity and decarbonisation. According to the IEA (2017a) 2 °C scenario (2DS) modelling, 26 EJ/yr of biofuels and 16 EJ/yr of electricity would consumed globally by transportation in 2050 (IEA, 2017a). Based on these estimates, we present three scenarios differing in terms of how by-product CO_2 from biomass processing is treated (labelled 'Vent' for venting to atmosphere, 'BECCS' for CO_2 capture and underground storage, and 'BECCU' for CO_2 capture and conversion to fuel). We also consider a fourth scenario (CCU Only), where biofuels are completely displaced by electrofuels. For the Vent scenario, emissions savings of 26% to 34% are achieved for 150g and 40g CO_2/kWh power sector emissions, respectively. When the by-product CO_2 is stored underground, emissions savings increase to 74% – 81% due to strongly negative biofuel emissions, greatly exceeding the 14% - 51% savings of the utilisation case. In the CCU Only scenario, the extent of decarbonisation becomes highly sensitive to power sector emissions – a 40 gCO_2/kWh system delivers 23 % savings, whereas 150 gCO_2/kWh actually leads to a 13% increase in emissions relative to 2010. Similar to Table 1, these results emphasise the need for ultra-low-carbon electricity if significant emissions savings are to be realised with electrofuels.

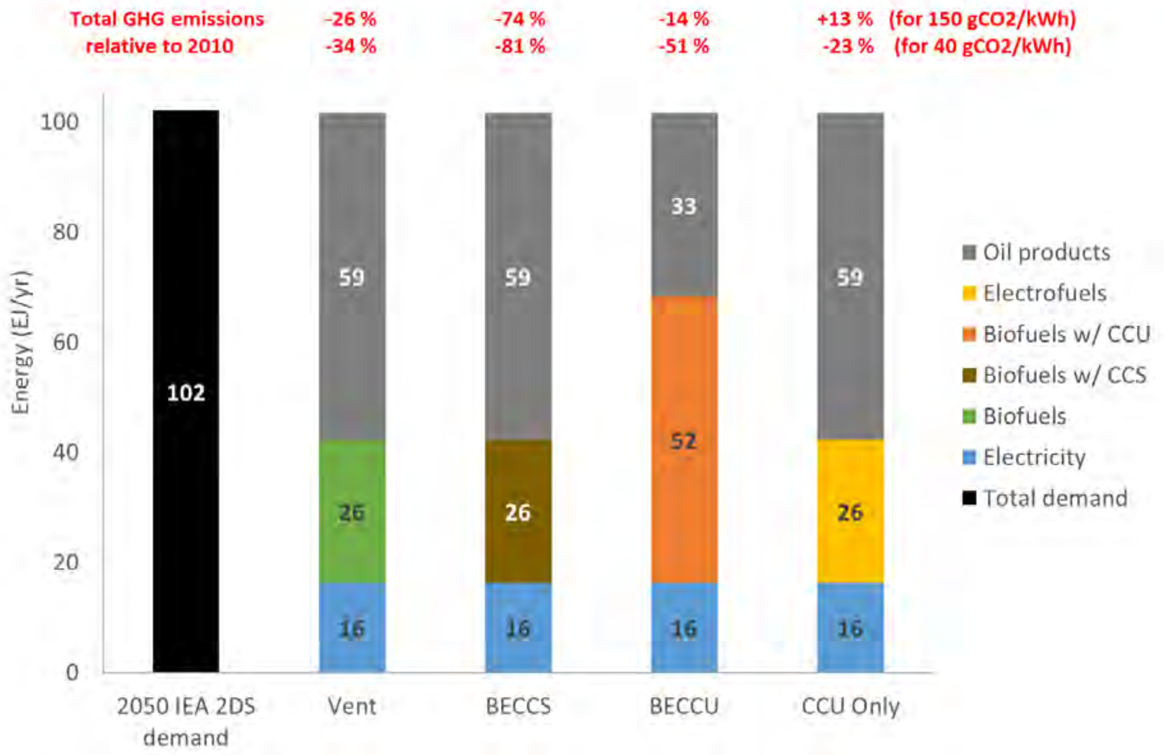

Figure 3. Global supply scenarios for 2050 and the resulting decarbonisation relative to 2010. Based on IEA 2DS modelling, the assumed carbon intensity of electricity is 40 gCO_2/kWh and the weighted average carbon intensity of fossil fuels is 72.7 gCO_2/MJ in 2050. Total emissions from transportation were 6.79 GtCO2 in 2010 (IEA, 2017a).

In the biofuel scenarios, primary bioenergy consumption never exceeds 52 EJ/yr, which is well below the IPCC (2014b) 100 EJ/yr estimate (medium evidence, high agreement) on technical biomass potential. However, a wide range of estimates of the availability of biomass for energy purposes are available in the literature, ranging from levels close to zero to well in excess of today's total energy use (1 500 EJ) (IEA, 2017c). Total electricity required is 16 EJ/yr for both the Vent and BECCS scenarios, while it increases substantially to 81 EJ/yr for the two electrofuel scenarios. Satisfying this larger demand would entail roughly tripling current global low-carbon electricity supply (~29 EJ/yr in 2015) (EIA, 2017) solely for transportation purposes, a formidable challenge on top of the contemporaneous need to fully decarbonise conventional electricity systems.

Setting Targets for CNSF

Although scaling up biofuels and electrofuels will differ greatly from battery technologies, much can be gained from emulating the visible BEV target setting effort. The US Department of Energy's $125/kWh target for 2022, first established in 2012 (USDOE, 2013), provides a benchmark for measuring progress. Moreover, manufacturers are in an intense competition for both customers and publicity, every announcement of the latest model's battery cost (such as Tesla's Model 3), brings with it additional scrutiny.

CNSFs, by contrast, have seen little visible competition and could benefit from establishing ambitious yet achievable targets in the near to medium term. Finland and Sweden, which have both pledged ambitious efforts to promote their bioeconomy, could be potential first movers (Staffas et al,. 2013; McCormick & Kautto, 2013), as could other leading biofuel nations such as Germany, Brazil and the United States (Hudiburg et al., 2016). Firms such as Audi or Bosch, which have pushed for larger-scale electrofuel plants, could provide private sector leadership. On biofuels, Lynd (2017) describes the need for a 'strategic reset'. The European Union, for example, is in transition from 2003-2012 era targets, which focused on traditional biofuels such as ethanol, to seemingly less ambitious targets, but which only permit more advanced biofuels (Skogstad, 2017).

Any CNSF target should help catalyse action, but need not fully achieve either economic parity or full decarbonisation. The DOE target for BEVs, for example, does not differentiate between a car charged in Wyoming, where the electricity mix is 970 kg/MWh or Vermont at 5 kg/MWh (EIA, 2016b). Like the battery target, any objective should be technology-neutral and agnostic as to whether breakthroughs happen with algae, fatty oils, wood chips or synthetic biology, as long as they meet basic sustainability standards (Savage, 2011). Blending obligations could encourage the volumes needed for scaling up, thereby encouraging learning. More generally, policy-makers may want to consider technology-neutral measures to tackle lifecycle or at least upstream emissions. The EU already has a declining emissions target for transport, but it only measures tailpipe emissions and so does not distinguish between an electric vehicle in Sweden versus Poland.

Industry may also benefit from having several parallel objectives – for example, although the focus is often on DOE's $125/kWh headline figure (from $500/kWh when announced), it also set targets for range of 250-300 miles (400-480 km) per charge and increasing battery lifespan to 15 years (from 8 years). Cumulative deployment is always the key to learning – Schmidt et al. (2017) find that battery pack capital costs are on a trajectory towards US$150-$200/kWh after a cumulative deployment of 1 TWh, which require investments of US$175–$510 billion and could be achieved by 2027–2040.

Conclusions

The tight coupling of vehicle fleet and refuelling infrastructure poses a barrier to large-scale introduction of any alternative. Melton et al. (2015) document over three decades of waves of failed hype cycles shifting across a half-dozen different transport alternatives. Currently, a number of developments would seem to augur well for BEVs, including the growing penetration of BEVs into the consumer market, adoption by a growing number of vehicle manufacturers and the parallel development of batteries at residential and grid scale, new mandates to phase out sales of petroleum-only vehicles as well as the potential for learning via hybrids, which allows for continued improvements even without mandating full BEVs (Nykvist and Nilsson, 2015). Nevertheless, important (and growing) segments such as air and sea transport will be challenging for batteries, so scaling up zero- or low-carbon fuel options will be essential over the coming decades so that they might be available as countries move up the marginal abatement cost curve and seek to decarbonise harder-to-abate sectors.

As CNSF technologies are currently pre-commercial, significant cost reductions might be expected as production capacity increases. However, due to long lead times, the short-term impact of CNSFs on transportation emissions remains limited. The biggest obstacle for electrofuels is not technology *per se*, which entails a simple integration of fairly well-known components, but cost and availability of ultra-low-carbon electricity. Whether electrofuels ever emerge as a viable decarbonisation option is governed by the prospects of future electricity markets. In the near-term, optimised ICEs (gasoline and diesel) are expected to be major contributors in the reduction of passenger car GHG emissions (Roland Berger, 2016). They are, however, limited in their ability to deliver ultra-low-carbon mobility, and ultimately, a combination of both low-carbon energy sources and alternative powertrains are needed.

All carbon-neutral options are currently very costly and so inevitably speculation abounds about technology evolution, learning potential and the nature of the support needed. Ultimately, improved cost forecasts and understanding the prospects of scaling up will be particularly valuable to policy-makers in making decisions on where to place their bets.

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Supplementary Materials

1. Calculation parameters and assumptions employed for comparing alternative CNSF configurations in Table 1.

As a starting point for our analysis, we consider the Audi e-gas plant (located in Werlte, Germany) as representative of the current state of electrofuels technology, and the GoBiGas plant (Gothenburg, Sweden) for synthetic biofuels technology. Both represent the largest plants of their kind that have been built and operated to date. Start-up of the Audi e-gas plant was in 2013, and produces 3.2 MW (LHV) of synthetic methane from 6 MWe electricity.[1] The total capital investment (TCI) was €20M [$22M based on a 1.1 $/€ exchange rate][2]. The GoBiGas plant began operations in 2013 and produces 20 MW (LHV) of synthetic methane from 30 MW_{th} (LHV) of lignocellulosic biomass. The TCI was 1494 million SEK (Swedish crowns)[3] [$178M based on an exchange rate of 8.4 SEK/USD].

The Audi e-gas and GoBiGas demonstration plants both produce synthetic methane, but with a different type of synthesis unit, the production of liquid hydrocarbons such as diesel (via Fischer-Tropsch synthesis, FTS) and gasoline (methanol synthesis followed by methanol-to-gasoline process, MTG) would be possible. Based on cost data from the GoBiGas installation, methanation equipment represented about 8 % of TCI.[3] While the FTS or MTG units are more complicated and thus probably more expensive than a methanation unit of comparable size, the impact on TCI is expected to remain small. However, the impact on fuel efficiency is more significant[4] and we adjust our parameterisation by assuming 50 % efficiency for liquid hydrocarbons from biomass (versus 67 % for GoBiGas) and 40 % for liquid hydrocarbons from CO_2 and water with electricity (versus 54 % for Audi e-gas), both being representative values based on following refs. [5, 6, 7, 8]. For electrolysis, an alkaline electrolyser operating at 65 % (LHV) efficiency to hydrogen is assumed.[9] High temperature electrolyser technologies would allow higher efficiencies - and are currently being developed - but are not yet commercially available beyond the scale of few hundred kilowatts. Carbon dioxide for the electrofuel process is captured from a point source, and the cost of the capture unit is included in the plant investment (Audi e-gas plant separates its CO_2 from biogas produced by an anaerobic digester). Reaction heat from the fuel synthesis is recovered, and used to provide the needed utilities for the plants, including process steam and regeneration of the CO_2 capture solvent.

As our cost data is derived from existing demonstration plants, it does not directly inform the economics of a future commercial-scale plant. Chemical process technologies are known to display strong economies of scale, and commercial synfuel plants (based on fossil feedstocks) operate at a scale of tens of thousands of barrels per day (see Table 1). For the production of biomass-derived CNSFs,

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[1] Otten, R. (2014). The first industrial PtG plant – Audi e-gas as driver for the energy turnaround. CEDEC Gas Day, Verona, Italy. http://bit.ly/2zTg5kW

[2] Rentzing, S. Audi fährt auf Wind ab. *Neue Energie* **2012/11**, 54-56 (2012). http://bit.ly/1nRgTwz

[3] Thunman, H., Larsson, A. and Hedenskog, M. (2015). Commissioning of the GoBiGas 20 MW biomethane plant. International Conference on Thermochemical Conversion Science, Chicago, USA.

[4] Hannula I. Co-production of synthetic fuels and district heat from biomass residues, carbon dioxide and electricity: performance and cost analysis. *Biomass Bioenerg.* **74**, 26-46 (2015). http://dx.doi.org/10.1016/j.biombioe.2015.01.006.

[5] Liu, G., Larson, E.D., Williams, R.H., Kreutz, T.G., & Guo, X. Making Fischer−Tropsch Fuels and Electricity from Coal and Biomass: Performance and Cost Analysis. *Energy & Fuels* **25** (1), 415-437 (2011). DOI: 10.1021/ef101184e

[6] Liu, G., Larson, E.D., Williams, R.H., & Guo, X. Gasoline from Coal and/or Biomass with CO2 Capture and Storage. 2. Economic Analysis and Strategic Context. *Energy & Fuels* **29** (3), 1845-1859 (2015). DOI: 10.1021/ef502668n

[7] Hannula I. Co-production of synthetic fuels and district heat from biomass residues, carbon dioxide and electricity: performance and cost analysis. *Biomass Bioenerg.* **74**, 26–46 (2015). http://dx.doi.org/10.1016/j.biombioe.2015.01.006.

[8] Hannula I. Hydrogen enhancement potential of synthetic biofuels manufacture in the European context: A techno-economic assessment. *Energy* **104**, 199–212 (2016). http://dx.doi.org/10.1016/j.energy.2016.03.119.

[9] L. Bertuccioli, A. Chan, D. Hart, F. Lehner, B. Madden, E. Standen, Study on development of water electrolysis in the EU, Final Report, Fuel cells and hydrogen joint undertaking (2014).

much smaller plants are usually proposed due to logistic, economic and sustainability constraints that pertain to the delivery of lignocellulosic biomass to a single central conversion facility. For an indication of a practical scale for a first-of-a-kind plant, we refer to biofuel projects awarded by the NER300 programme – a European Commission policy instrument for co-funding commercial-scale carbon capture and storage (CCS) and innovative renewable energy technologies (IRT) demonstration projects (where NER300 refers to the 300 million emissions allowances from the so-called new entrants' reserve (NER) that had been set aside for potential entrants but which were to be auctioned off to fund the support programme).[10] Four synthetic biofuel projects (see Table 2) were initially awarded funding by the programme between 2012 and 2014, although none of the projects have yet been realised (as of Dec 2017). The median scale of the successful synthetic biofuel projects was 160 $MW_{synfuels}$ (~2500 barrels per day). We adopt this as the scale of our first-of-a-kind commercial-scale plants. Although the size of electrofuels plants is not similarly constrained than biofuel plants, we adopt the same scale also for electrofuels plants to ensure that both technologies enjoy scale benefits by the same measure. Considering conversion efficiency, 160 MW synfuel output leads to 320 MW (LHV) biomass input for the synthetic biofuel plant and 400 MWe electricity input for the electrofuels plants.

Table S1. Capacities of operating commercial-scale synfuel plants producing Fischer-Tropsch liquids.[11]

Country	Plant	Start-up	Feedstock	Capacity, b/d
South Africa	Sasol I, Sasolburg	1955	brown coal*	8 000
	Sasol II, Secunda	1980	coal	64 000
	Sasol III, Secunda	1983	coal	96 000
	Mossgas, Mossel Bay	1991	natural gas	22 500
Malaysia	Bintulu GTL, Bintulu	1993	natural gas	14 700
Qatar	Oryx GTL, Ras Laffan	2006	natural gas	32 400
	Pearl GTK, Ras Laffan	2011	natural gas	140 000
Total				377 600

*Syngas for the Sasol-1 plant was produced from brown coal produced locally. Since 2004 syngas at Sasol-1 plant has been manufactured from natural gas delivered by pipeline from Mozambique.

We use a cost scaling exponent (k) to scale the cost (C_0) of the demonstration plant to commercial scale (S) using the following relationship: $C = C_0*(S/S_0)^k$, where S_0 is energy input [MW] of the demonstration plant, and C is the TCI estimate [M$] for a similar plant at commercial scale. Traditionally, k is assumed to have a value between 0.6 and 0.7 for chemical processes.[12] For the purposes of this study, we use an average value of k = 0.65 for synthetic biofuel technology. For modular technologies, k = 0.9 is often used (k<1 is justified because the installed cost of each additional unit will be somewhat less than the cost for the first unit, since multiple units typically share some auxiliary equipment, and as the installation labour per unit is less than that for a single unit, etc.). On a process level, we assume electrofuel plants to be at least partly modular, since they are likely to be based on multiple electrolysers in parallel rather than one or a small number of very large electrolyser units (for example, the 6 MW_e Audi e-gas plant, already features three 2 MW_e electrolysers). We expect the electrolyser investment to represent roughly one third of the Audi e-gas plant TCI (based on ~€1000/kW_e investment cost estimate for alkaline electrolysers[9]), and thus we estimate that the weighted average k is (1/3*0.9+2/3*0.65=) 0.73 for electrofuels technology.

We calculate the levelised cost of fuel (LCOF), assuming 8 % weighted average cost of capital (WACC) and a 20-year economic lifetime for the investment. The annual operating and maintenance costs are assumed to be 2 % of TCI for electrofuels and 4 % of TCI for the synthetic biofuel plant. No co-product revenues are considered, although they might represent significant additional sources of income for

[10] Balan, V., Chiaramonti, D., & Kumar, S. Review of US and EU initiatives toward development, demonstration, and commercialization of lignocellulosic biofuels. *Biofuels, Bioproducts and Biorefining*, **7**(6), 732-759 (2013).
[11] Glebova, O. Gas to Liquids: Historical Development and Future Prospects. Oxford, Oxford Institute for Energy Studies (2013).
[12] Remer, D.S. & Chai, L.H. "Process Equipment, Cost Scale-up," *Encyclopedia of Chemical Processing and Design*, ed., McKetta, J., Marcel Dekker, Inc., 43, 306-317, (1993).

individual plants that can sell their by-product heat, process steam and/or electricity (plus a small amount of propane and butane for MTG configurations).

Table S2. Synthetic biofuel projects awarded funding by NER300.

Project name	Member state	Project Sponsor	Fuel output		Funding	
			kton/a	MW	M€	€/MWh
Ajos BTL	Finland	Forest BtL Oy	150	229	88	17
GoBiGas, phase 2	Sweden	Göteborg Energi	50	87	59	20
UPM Stracel BTL	France	UPM-Kymmene	105	160	170	37
Bio2G	Sweden	E.ON	115	200	204	37

We express the LCOF as a breakeven oil price (BEOP, \$/bbl), which represents the crude oil price at which the LCOF is the same as the refinery-gate price for crude oil-derived liquid hydrocarbon (we use 1.22 wholesale fuel price multiplier and 33.2 MJ/l energy intensity for liquid hydrocarbons, being average values between gasoline and diesel). Table 1 compares different CNSF alternative assuming that carbon emissions are not taxed. Table S3 (below) presents same analysis, but under the assumption that carbon emissions are taxed at \$100/tCO2.

Table S3. Comparison of breakeven oil prices (BEOP, $/bbl), GHG balances and abatement costs of alternative CNSF configurations. Cost estimates based on demonstration plant data and developed for first-of-a-kind plants that produce liquid hydrocarbon fuels at 160 MW (~2500 barrels per day) scale. $100/tCO2 carbon price assumed.

CNSF plant configuration	Capacity factor	Energy cost[a] $/MWh	BEOP[b] $/bbl	Electricity gCO2/kWh	End-product gCO2/MJ	Relative emissions[c]	Abatement cost, $/tCO2[d]	Carbon tax, $/l
Synthetic biofuels[e]	85%	8 – 24	107 – 146		5	7 %	153– 256	0.4 – 0.6
Generator connected electrofuels[f]								
Nuclear	90%	112 – 183	361 – 574	3.7	3	3 %	803 – 1354	2.0 – 3.4
Geothermal	85 – 90%	77 – 117	256 – 376	6	4	5 %	544 – 862	1.4 – 2.2
Solar Thermal Tower + Storage	43% – 52%	98 – 181	361 – 610	8.8	6	8 %	844 – 1521	2.1 – 3.8
Solar PV - Utility scale								
Crystalline	21 – 30%	46 – 53	278 – 299	18	13	16 %	681 – 744	1.7 – 1.9
Thin film	23 – 32%	43 – 48	258 – 273	18	13	16 %	622 – 667	1.6 – 1.7
Wind								
Onshore	38 – 55%	30 – 60	151 – 241	7	5	6 %	268 – 509	0.7 – 1.3
Offshore	40 – 50%	71 – 155	283 – 536	8	6	7 %	628 – 1308	1.6 – 3.3
Grid connected electrofuels[g]								
EU-28	90%	114	500	447	310	410 %	No abatement	-
Germany	90%	149	656	615	427	564%	No abatement	-
France	90%	89	322	105	73	96%	17614	41.6
Sweden	90%	66	235	47	33	43%	812	1.9
Norway	90%	81	269	9	6	8 %	596	1.4

Notes:

a) *Biomass residues for advanced biofuel plant, electricity for electrofuel plant. Delivered cost of biomass feedstock $40 - $120/dry ton (assuming 19 MJ/kg lower heating value) from US DOE 2016 Billion-ton report figure ES.8, cost of electricity for different energy sources from Lazard's Levelized cost of energy analysis – version 11.0 (2017). Grid costs from Eurostat data for industrial consumers in 2016 including taxes and levies but excluding VAT.*

b) *Break-Even Oil Price. Assumptions used for all plants: 160 MW (LHV) liquid hydrocarbon output, wholesale fuel price multiplier 1.22, 20 yr economic life, 8% WACC, For an electrofuel plant producing liquid hydrocarbon: 40 % (LHV) fuel efficiency, $479M total capital investment (TCI), annual operating and maintenance cost 2 % of TCI. For a biofuel plant producing liquid hydrocarbons: 50 % (LHV) fuel efficiency, $828M total capital investment (TCI), annual operating and maintenance cost 4 % of TCI.*

c) *Lifecycle GHG emissions associated with the facility divided by lifecycle emission of fossil-derived product displaced. Carbon content of liquid hydrocarbons: 2.52 kgCO_2/L.*

d) *Based on $50/bbl crude oil price.*

e) *End-product GHG emissions for synthetic biofuels (average based on farmed wood and waste wood) from JEC (2014).*

f) *Minimum lifecycle emissions (incl. albedo effect) for selected electricity supply technologies from IPCC (2014) Annex III: Technology-specific cost and performance parameters, Table A.III2.*

g) *Carbon intensities of electricity consumed at low voltage section of the electric network including upstream emissions in 2015 from Moro and Lonza (2017).*

2. Calculation parameters and assumptions employed for calculating equal-cost curves for Figure 2.

To calculate the equal-cost curves in Figure 2 we adopt an approach similar to that developed in Newbery and Strbac (2016)[13], which seeks to strip out all the various distortions that often bedevil comparisons between battery electric vehicles (BEVs) and internal combustion vehicles (ICVs), by applying the techniques of social cost benefit analysis to the comparison and integrating this with electricity supply modelling. Equal-cost (cost parity) means that, at the very least, the "fuel" cost of the BEV should be no higher than that of comparable ICVs, where the "fuel" cost includes not only the electricity cost but also the interest and depreciation of the battery, as that is an essential but additional part of EV power delivery. Newbery and Strbac consider this to be a minimal requirement since there are additional hurdles that BEVs would need to overcome; of which limited range and slow charging rates are the most obvious. Also, using efficient rather than tax-inclusive market prices has significant impact on the relative costs of ICVs and BEVs, as there are huge differences between the efficient price of road fuel and its retail price. Figure 2 shows equal-cost curves for gasoline vehicles. Figure S1 (below) shows equal-cost curves for diesel vehicles.

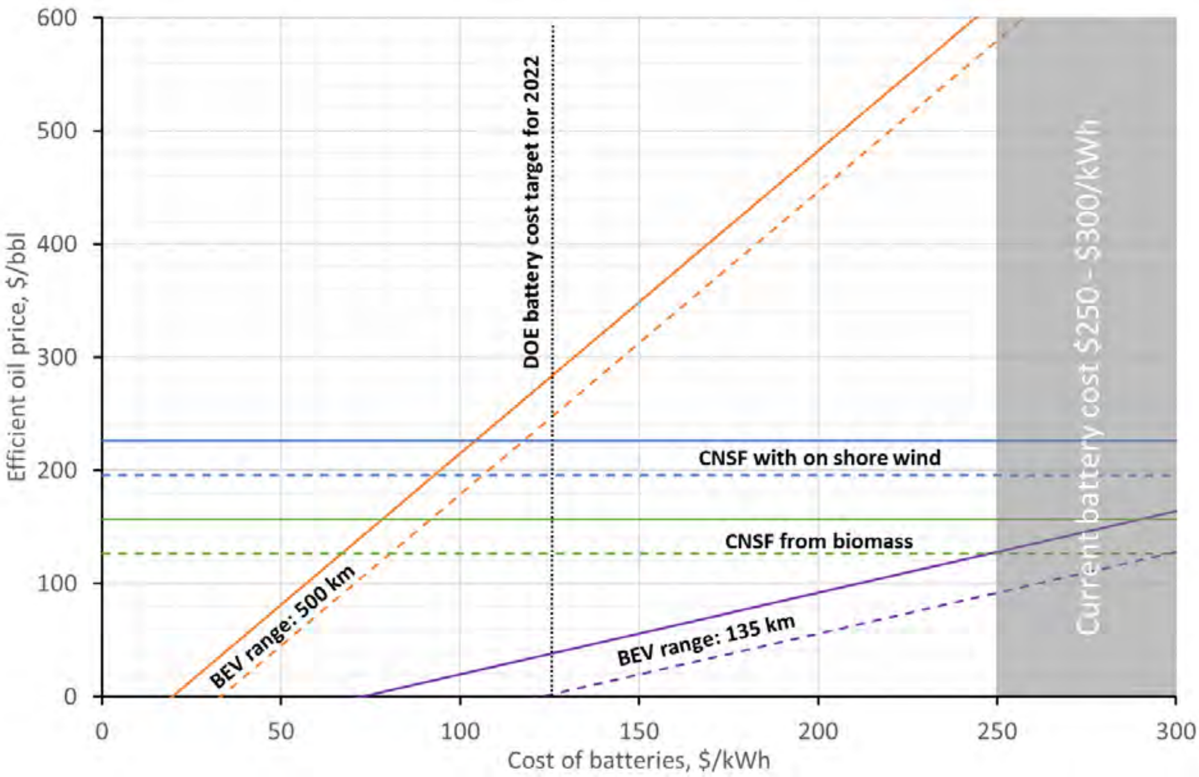

Figure S4. Relationship between fuel and battery costs such that the total social cost of using CNSFs in a diesel vehicle equals the total social cost of owning and operating an electric vehicle. Carbon emissions are assumed to be taxed at \$0/tCO2 for the continuous lines and \$100/tCO2 for the dashed lines.

Based on the vehicle assumptions for 2020 in Newbery and Strbac (2016), we use \$0/tCO_2 and \$100/tCO_2 as emission costs, 1.26 for the wholesale gasoline price multiplier (1.18 for diesel in Fig. S1), 7 c/l gasoline retail margin (9 c/l for diesel), 2.36 gCO_2/l gasoline carbon content (2.68 gCO2/l for diesel), and 3 c/l gasoline pollution cost (9 c/l for diesel). The BEV battery is sized to allow either 135 or 500 km single-charge range, while assuming 10-year vehicle life and 170,000 km lifetime battery range (17,000 km annual distance travelled). Electric motors convert 75% of the energy supplied into the batteries to power the wheels and move the vehicle 5 km per every kWh supplied. For gasoline vehicles, 30 % efficiency is assumed (35 % for diesel vehicles in Fig. S1). We assume savings from a

[13] Newbery, D. & Strbac, G. What is needed for battery electric vehicles to become socially cost competitive? *Economics of Transportation* **5**, 1-11 (2016). https://doi.org/10.1016/j.ecotra.2015.09.002.

BEV drivetrain relative to ICV to be $750, while a home charger costs $800. The cost of electricity is 13 cents per kWh assuming smart charging (70% off-peak & 30% peak), and the discount rate is 8%.

According to Nykvist and Nilsson (2015)[14], the cost of battery packs used by market-leading BEV manufacturers were US$300 per kWh in 2015, and have been declining by 8% annually. Based on these findings, we assume that the cost of battery packs today (2017) are within the range of $250 – $300/kWh.

3. Additional notes for supply scenarios in Figure 3.

Significant quantities of biomass residues are available today from agricultural and forestry operations,[15,16] and could be used for the production of synfuels. Considerable uncertainty however exists about the limits of supply. The review by Ahlgren et al. (2017)[17] finds that half of biomass availability studies use 200 EJ/yr as an upper bound, one-third use 300 EJ/yr and above and the remainder assume a 150 EJ/yr maximum. Although these studies all offer a generous technical potential, their estimates of the actual supply available by mid-century varies widely – from 2 – 50 EJ/yr – which highlights the large uncertainty in medium-term estimates of availability.

Although numerous individual niche opportunities have been identified, studies of the overall potential for CCU in general have been sceptical of its potential given the relatively limited availability of low-cost options such as enhanced oil recovery. Mac Dowell et al. (2017)[18] come up with an estimate of 15.42 Gt carbon dioxide utilized by 2050 across all forms of utilisation, of which 3.86 Gt_{CO2} would be sequestered—about 0.49% of the 800 Gt_{CO2} mitigation challenge. Kolster et al. (2017)[19] find that current levels of CO_2 and oil prices and inadequate for a scaling up EOR to a one gigatonne-scale, and even that level of deployment would require either an oil price above $85 per bbl or a carbon tax of $70/t CO_2 (relatively modest by the standards of our analysis)

Electrofuels would impose enormous requirements on power systems. According to Hansson et al. (2017)[20] the potential for electrofuels production in Sweden utilising both fossil and biogenic CO_2 point sources is 2–3 times the current Swedish demand for transportation fuels, while the electricity required would correspond to about three times the current Swedish electricity supply. We expect a similar scale of power required to apply also for other industrialised countries.

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To be consistent with IEA modelling in Figure 3, we follow UNFCCC accounting procedures where biofuels are considered to have net zero carbon emissions. For the BECCS scenario, we calculate the negative GHG emissions of biofuels based on mass and energy balances from Liu et al. (2011)[21] for Fischer-Tropsch fuels (mainly diesel) and Liu et al. (2015)[22] for synthetic gasoline (see Table S4).

Table S4. GHG emissions calculation for liquid hydrocarbons from biomass when the by-product CO2 from biomass processing is sequestered underground (BECCS scenario).

	F-T fuels*	Synthetic gasoline**
CO2 captured from plant, kgC/s	-9.469	-9.8
CO2 captured from plant, kgCO2/s	-35	-36
Fuel output from plant, MW (LHV)*	283	287
Specific emissions of produced fuel, gCO2/MJ	-123	-126

*CO2 capture rate and fuel output from Liu et al. (2011) Table 4 for configuration BTL-RC-CCS.
** CO2 capture rate and fuel output from Liu et al. (2015) Table 7 for configuration BTL-RC-CCS.

Based on the results of our calculations, an average value of -124 gCO2/MJ is used for biofuels in the BECCS scenario.

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