What will fuel transport systems of the future?

This paper seeks to decry the notion of a single solution or "silver bullet" to replace petroleum products with renewable transport fuel. At different times, different technological developments have been *in vogue* as the panacea for future transport needs: for quite some time hydrogen has been perceived as a transport fuel that would be all encompassing when the technology was mature. Liquid biofuels have gone from exalted to unsustainable in the last ten years. The present flavor of the month is the electric vehicle. This paper examines renewable transport fuels through a review of the literature and attempts to place an analytical perspective on a number of technologies.

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When discussing energy, it is important to understand the relevant units. Box 1 outlines the relationship between the *tonne of oil equivalent* (toe), the Joule, and the GW_eh. In addition, primary and final energy must also be differentiated, particularly for electricity. Primary energy is the energy contained in primary resources prior to conversion or transformation into a form that is used by the final consumer. Energy used by the final consumer is final energy. For example the energy content of the coal used in a power plant is primary energy while final energy describes the electricity produced by the power plant. The ratio of primary energy to final energy is approximately 2.5 if electricity is produced at 40 % electrical efficiency. This relationship is less clear for renewable sources. For example, for wind power primary energy is similar to the final energy.

Background and perspective

The world's Total Primary Energy Supply (TPES) was 514 EJ (12 267 Mtoe) in 2008, which is double the figure of 1973 (256 PJ)[1]. In 2008 renewable sources accounted for 12.9 % of the TPES. On a global scale the ratio of primary energy to final energy was 1.47[1].

There tends (particularly in the media) to be a preoccupation with renewable electricity rather than renewable energy. Electricity consumption in 2008 equated to 60.6 EJ or 17.2 % of the Total Final Consumption (TFC) while transport equated to 95 EJ or 27 % of the TFC[1]. On a global scale 18.7 % of the electricity is produced from renewable sources; the majority of which is from hydro-electricity (15.9 %). Renewables play a smaller role in transport. In 2008 liquid biofuels accounted for 1.92 EJ or about 2 % of the energy used in transport[2]. This relatively small proportion has been controversial,

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Box 1 Energy units and prefixes

At a national or global scale, energy may be described in:
PJ (10^{15} J) or EJ (10^{18} J).
Alternatively, Million tonnes of oil equivalent (Mtoe) may be used.
1Mtoe = 41.9 PJ.
Electricity may be described by the TW_eh (1 TW_eh = 3.6 PJ).
1 kW_eh = 3.6 MJ.

k = 10^3: M = 10^6: G = 10^9: T = 10^{12} :P = 10^{15}; E = 10^{18}.

leading to a food versus fuel debate[3,4]. In 2007 – 2008 the prices of wheat, rice, and maize increased by 130 %, 98 %, and 38 % respectively; this was attributed to the maize ethanol market[5]. This may indicate that we need to worry about transport fuels of the future.

Land, population, food, biomass, and biofuels

If biofuels are a solution to renewable transport fuel we must consider the available land. The land area on Earth is 149 × 10^6 km^2; 55.7 % of this is forest, 16.1 % (or 24 × 10^6 km^2) is pastureland and 9.4 % (or 14 × 10^6 km^2) is arable land[6]. The population of the world is growing. In 1804 there were 1 billion people on the planet; in 2000 this number had increased by a factor of 6. By 2013 another billion people will occupy the planet[7]. Global arable land averages only 0.2 ha per person and this number is decreasing. Life styles are such that more people require meat. A meat diet requires more land than a vegetarian diet. Thus our finite agricultural land is required to produce more food for a growing population of humans and animals as well as renewable thermal and transport energy. Is this possible?

Ireland: a case study

The world is variable; bioenergy systems are geography specific. Sugar cane grows in tropical climates not in temperate ones. Even in particular climatic regions the yield of crops varies; maize for example provides yields in the range of 9 to 30 tonnes of dry solids (tDS) per hectare per annum[8]. This paper will use Ireland as an example where necessary. The Republic of Ireland is part of the island of Ireland and is situated at the western extreme of Europe. It has a population of

Table 1 Forecasted final energy consumption in Ireland in 2020. Adapted from[11].

	PJ	% total
Electricity	124	21.5
Thermal	223	38.9
Transport (road and rail)	188	32.8
Other transport (not covered by RES-T)	39	6.8
Total	574	100

Box 2 The role of EVs in renewable energy

Renewable energy associated with EVs

300 000 EVs in 2020, each travelling 16708 km/a.
5 billion km/a at a fuel efficiency of 6 km/kW_eh = 835 GW_eh/a or 3 PJ/a.
Final energy consumption for transport Ireland in 2020 is projected to be 188 PJ.
300 000 EVs equates to 1.6 % of the energy in transport (2.4 % of the energy in electricity).
The target for green electricity in 2020 is 40 %.
300 000 EVs equates to 0.64 % green energy in transport.

The relationship between EVs and 3 MWe turbines

Allowing for 8 % losses between the source and plug in point, and a 12 % loss from plug to battery[14], a 3 MW_e wind turbine at a capacity factor of 30 % generates:
3 MW_e × 8760 h/a × 0.3 × 0.92 × 0.88 × 10^{-3} = 6.38 GW_eh/a.
300 000 EVs require 3 PJ or 835 GW_eh/a.
One hundred and thirty one 3 MW_e wind turbines would be required.
One 3 MWe turbine will fuel about 2300 EVs.

4.5 million and a land area of 6.8 million ha. The agricultural area is of the order of 4.4 million hectares of which 4 million are deemed pastureland (including rough grazing) and 400 000 hectares are arable[9].

Energy forecasts for Ireland

Ireland is a member state of the EU. The EU has set targets for Ireland of 16 % renewable energy supply (RES) in 2020. They have further set a specific target of 10 % renewable energy supply in transport (RES-T)[10]. Policy in Ireland has a particular focus on renewable electricity (RES-E). Ireland has independently set a target of 40 % RES-E; this will be met predominately through wind power. Ireland's forecast for total final energy in transport in 2020 (allowing for the implementation of energy efficiency and renewable energy plans) is 188 PJ[11] (Table 1). In 2008 Ireland had 2.497 million vehicles of which 1.92 million were private cars. The private car density thus equated to ca. 430 per 1000 population, with an average annual distance travelled of 16 708 kilometers[12].

Contribution of electric vehicles to renewable transport

The role of electricity in renewable transport

Electric vehicles (EVs) are expected to make a significant impact on the international transport fleet with several manufacturers rolling out EV models. The EV (Fig. 1) is recharged from the electricity grid and is not only beneficial to the vehicle users, but also to electricity providers. EVs can act as an energy storage system by recharging at night when

(a)

(b)

Fig. 1 (a) Wind turbine and (b) plug-in electric vehicle.

the electricity demand is normally low and electricity from wind may otherwise be wasted. The primary disadvantage of the EV is the battery, which has a relatively short lifetime, a long recharging time and results in a short driving distance per charge.

The proposed role of EVs in Ireland

The Irish Government has set an ambitious target of 10 % of all vehicles in the transport fleet to be powered by electricity by 2020. This will require between 250 000 – 300 000 EVs[12]. With reference to Box 2 it may be noted that this amounts to only 1.6 % of the energy in transport and as only 40 % of electricity is proposed to be green, accounts for only 0.64 % RES-T. The EU Renewable Energy Directive[10] allows a weighting of 2.5 to green electricity, thus this again equates to 1.6 % RES-T. The rationale for this weighting is to incentivize EVs, but there is some logic to this value as it is similar to the ratio of primary energy to final energy. The value of 1.6 % RES-T is very similar to values obtained by Foley and co-workers[13].

EVs as a variable electricity storage mechanism

One issue with producing electricity from wind is its intermittency and the inability to store it on a large scale. Much of the potential electricity that could be produced by wind at night is lost to the system. Electricity demand in Ireland is expected to be 124 PJ in 2020 (Table 1) and 40 % of this (ca. 50 PJ) is targeted to be renewable; as wind is the dominant renewable energy source, the production will be variable. On a very simplified basis it can be assumed that a third of this electricity (ca. 17 PJ) will be produced by night when demand is very low. The 300 000 EVs plugged in at night will require 3 PJ/a; averaged over the year EVs could store on the order of 18 % of the electricity produced from wind during the night.

On the most advantageous sites in Ireland a wind turbine will generate electricity at a 40 % capacity factor; as more turbines are built this has dropped to ca. 30 %. With reference to Box 2 it may be noted that a 3 MW_e turbine can provide electricity for 2300 EVs; one hundred and thirty one 3 MW_e turbines are required to fuel 300 000 EVs. It is obvious that although EVs have a significant role to play in renewable energy, other sources are required.

Liquid biofuels

Liquid biofuels are dominated by bioethanol and biodiesel. Approximately 67 billion liters of bioethanol were produced in 2008[9]. This equates to 1.4 EJ or (1.47 % of the energy in transport). Approximately 12 billion liters of biodiesel were produced in 2008[9] (400 PJ or 0.42 % of the energy in transport).

Bioethanol

Bioethanol may be produced from sugars (sugar cane, sugar beet) or starches (corn/maize, wheat, barley). Ethanol production requires fermentation of six-carbon sugars with *saccharomyces cerevisiae* as the prime yeast species[15]. Sucrose ($C_{12}H_{22}O_{11}$) can be easily converted to glucose and therefore juice or molasses from sugar cane and sugar beet do not require hydrolytic pre-treatment[16]. Starch however is a complex carbohydrate $(C_6H_{10}O_5)_n$ which requires hydrolytic pre-treatment prior to fermentation[17]. Starch is the most utilized feedstock for ethanol production[16]; its conversion is energy intensive[18]. For example wheat ethanol has a by-product known as wet distiller's grain and solubles (WDGS) which contains 33 % of the starting solids at ca. 12 % solid content. It is used as cattle feed after drying to 9 % water content. This drying process can account for up to 35 % of the total parasitic thermal demand of the ethanol process[18].

Biodiesel

Biodiesel is produced from rapeseed and sunflower in Europe, soybean in Southern America, and palm oil in South East Asia. It is produced through a transesterification process whereby oil (ca. 90 %) and methanol (ca. 10 %) together with a catalyst are converted to fatty acid methyl ester (FAME) or biodiesel (ca. 90 %) and glycerol

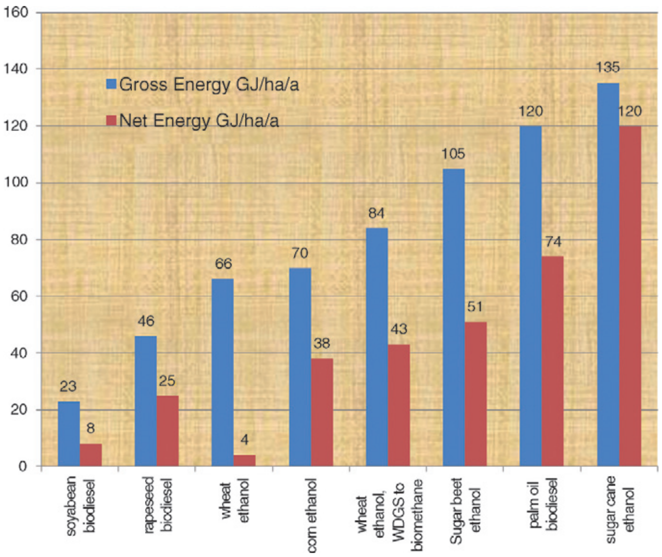

Fig. 2 Gross and net energy balance of selected biofuel systems. Adapted from[9].

(ca. 10 %). Physical properties of the specific oil depend on the portion of triglycerides and free fatty acids (FFA). For example, fresh vegetable oils comprise 90 – 98 % triglyceride with a small portion of FFA[19,20] while used cooking oil is high in FFA content. Two production methods are currently available at commercial scales[21]: (1) Alkaline catalyzed transesterification; (2) Acid and alkaline catalyzed transesterification in a two-stage process.

The first method is used to transesterify oil with low FFA content; the process can be established on a small scale. The second method is for oils high in FFA. The two-stage process begins with an esterification reaction using an acid catalyst to convert FFA into biodiesel; subsequently a transesterification reaction (method 1) is used to convert the remaining triglyceride into biodiesel. Animal fat obtained from the rendering process and used cooking oil from catering are normally high in FFA content, and require the two-stage technology.

Sustainability of first generation biofuels

Issues related to liquid biofuels may be separated into energy balances and green house gas analyses.

Energy balance

Gross energy reflects the yield of biofuel per hectare. The net energy deducts the energy input to the crop production and to the process. For example, 18 GJ of direct and indirect energy is required per hectare to produce wheat. Indirect sources include the energy required to produce the fertilizers. Direct energy includes diesel to power agricultural machinery[22].

In wheat ethanol approximately 66 GJ of ethanol are produced per hectare in Ireland (372 L ethanol / tonne of grain × 8.4 tonnes of grain / hectare × 21.1 MJ / L of ethanol). However in a standard ethanol system using electricity from the grid powered by fossil fuel and natural gas for thermal energy about two thirds of the output energy is used in the process[18]. Thus wheat ethanol has a gross energy of 66 GJ/ha/a (3125 L of ethanol per hectare) while the net energy can be as low as 4 GJ/ha/a (Fig. 2). This highlights one difference between modern biofuel facilities in the developed world and those in the developing world. Sugarcane ethanol facilities use the residue of the cane (bagasse) as a source of combined heat and power to fuel the system and as such the net energy is not much lower than the gross energy (Fig. 2). Systems can always be improved. Murphy and Power[18] showed that by using stillage (WDGS) to produce biomethane, and straw as a source of thermal energy, the gross energy of the bioenergy system could be increased by 27 % and the net energy from 4 to 43 GJ/ha/a. For an optimum sized ethanol facility (150 million liters / annum) the land under grain (and straw) is 48 000 ha. As straw is a bulky, voluminous biomass the developer may find this logistically difficult and expensive. How is the developer persuaded to be sustainable?

Table 2 Typical values for greenhouse gas savings from the EU renewable energy directive. Adapted from[10].

Biofuel system	% savings in greenhouse gas emissions as compared to fossil fuel replaced
Wheat ethanol	32
Rape seed biodiesel	45
Sunflower biodiesel	58
Sugarcane ethanol	61
Palm oil biodiesel	62
Biogas from MSW	80

Greenhouse gas balance

A greenhouse gas balance outlines the sustainability of the biofuel system. The EU Renewable Energy Directive[10] states that to be deemed sustainable the biofuel system must affect a 60 % saving in greenhouse gas emissions compared to the displaced fossil fuel. Table 2 highlights data from the Directive for various biofuel systems. A lot of negative energy balances and life cycle analysis have been attributed to biofuel systems as non-biofuel products are neglected in the analysis. Fig. 2 only allows for energy in fuel. If, for example, the stillage from a grain ethanol facility is fed to cattle and displaces grass silage, no credit is given to the ethanol system. The present authors[23] investigated biodiesel for use in Ireland through comparison of indigenous Irish rape seed and palm oil biodiesel produced in Thailand. The paper highlighted the benefits of the palm oil system as the by-products provide the parasitic energy demand of the palm oil biodiesel system. The paper also highlighted a short fall in the analysis of biofuel systems in the developed world. Of the 4 tonnes of rape seed produced, 1.2 tonnes is converted to biodiesel while 2.8 tonnes is converted to rape cake[23]. A further paper by the same

Table 3 Land required to meet the 2010 biofuels target in Ireland. Adapted from[25].

Biofuel		Land take (kha/a)	% of agricultural land	% of arable land (9 % of agricultural land is arable)
Biodiesel	Rape seed	279.1	6.3	70
Ethanol	Wheat	172.3	3.9	43
Ethanol	Sugar beet	107.1	2.4	26

Table 4 Comparison of hydrogen and methane as sources of transport fuel.

	Hydrogen	Methane
Energy value	142 MJ/kg	55.6 MJ/kg
Molecular weight	2.016	16.042
Density	0.085 kg/m_n^3	0.677 kg/m_n^3
Energy value	12.1 MJ/m_n^3	37.6 MJ/m_n^3
Compression	700 bar	220 bar
Energy per unit compressed storage	8.47 MJ/L	8.27 MJ/L
Energy to compress	13 %	3.3 %

authors[24] found that allocation by energy content attributes almost half the greenhouse gas emissions to rape cake (a co-product). Rape cake substitutes for importation of soybean from South America and thus saves on emissions through deforestation and/or ploughing of grass lands. They found that the system could be sustainable when produced glycerol is used as a source of heat, and rape straw pellets are used *in lieu* of peat (an environmentally damaging indigenous fuel source in Ireland).

Bioresources of first generation biofuels in Ireland

Murphy and Power[25] highlighted the quantity of land required to meet the 2010 5.75 % biofuel target for Ireland. The fuel required equated to 11.3 PJ/a or 538 million L/a of ethanol or 323 million L/a of biodiesel. The land take is excessive. With reference to Table 3, rape seed, which is a one in four year rotational crop, requires 280 % of the arable land involved in a rape seed rotation to meet the 5.75 % biofuel target. This is not possible.

Second generation biofuels

Second generation biofuels are derived from lignocellulosic feedstocks. These feedstocks do not (directly) compete with food production but may compete for resources such as water and land. Thus indirectly there is potential for conflict with food if lignocellulosic crops (such as *Miscanthus*) are grown on arable land. The beneficial use of whole crop (straw and cereal) for biofuel production has a drawback in that carbon that may have been ploughed back in (in the form of straw) is now not available. This can lead to carbon depletion of the soil. Care must be taken that carbon is recycled to the soil where lignocellulosic biomass is produced. In the long term it must also be noted that fertilizer is dependent on fossil fuel, and as fossil fuels deplete, fertilizer will become very expensive.

Lignocellulosic biomass typically comprises 35 – 50 % cellulose, 15 – 25 % hemicellulose, 15 – 30 % lignin and small amounts of extractive substances and ash[26]. Bio-refineries convert lignocellulosic biomass into biofuels and smaller quantities of high value products (e.g., chemicals)[27]. Two particular issues require caution with regard to assuming that second generation biofuels are superior to first generation biofuels, namely: the feedstock and the process. Second generation biofuels are not always free or cheap. In 2006 – 2007 grain prices were of the order of €110/t in Ireland[28]. Straw, for example, is a second generation feedstock with a yield of ca. 5 t/ha/a (compared to ca. 8.5 t/ha/a of wheat grain)[28]. Straw requires collection, baling, and transport and has a minimum cost of ca. €65/t[29]. In Denmark straw is used in CHP facilities, which drives up the price further[29]. Straw is voluminous and bulky and as such has high transport costs for the high distances associated with a commercial ethanol facility. It produces 37 % of the ethanol produced by grain per unit mass (140 L/t versus 372 L/t)[30] and as such should be at a maximum 37 % the price of grain. The process for production of straw ethanol requires a pre-treatment step before the first generation technology[30]. This is typically a steam explosion step which drives up the capital and operating costs.

Hydrogen

Hydrogen is seen as a clean, abundant energy source with water vapor as the only emission in combustion. The merits of hydrogen are based on the fact that its energy content per unit mass is very high. The demerit of hydrogen is that its energy value per unit volume is low. If we consider diesel has an energy value of ca. 37 MJ/L then 1 L of diesel has an energy content similar to 1000 L of methane and 3000 L of hydrogen (Table 4). Hydrogen tends to be bound in compounds such as water or in hydrocarbons such as gas. To be used as an energy source it has to be separated from carbon in gas or oxygen in water. Typically hydrogen is produced using two methods.

Steam reforming of natural gas

Approximately 95 % of hydrogen used in the United States is generated from natural gas[31]. Steam is used to reduce methane to hydrogen and carbon dioxide. The energy demand is of the order of 20 to 30 %[32]. Carbon dioxide may be removed through pressure swing adsorption and ideally carbon should be captured and stored. Hydrogen from steam reforming will always be more expensive than natural gas.

Water electrolysis

For renewable hydrogen, renewable electricity must be sourced. The energy efficiency of commercial electrolyzers is ca. 74 %[33]. This value refers only to the efficiency with which electrical energy is converted into the chemical energy of hydrogen. Distribution losses of 4 – 8 % must be added [34].

(a)

(b)

(c)

Fig. 3 (a) Facility producing biomethane from waste food in Austria. (b) Upgrading of biogas and injection of biomethane into the natural gas grid (yellow valve centre of picture) in Austria. (c) Injecting biomethane into a bus in Linkoping, Sweden.

Hydrogen versus natural gas

Why convert methane (natural gas) to hydrogen to use as a transport fuel? The natural gas system in Ireland is extensive, is interconnected to the European gas network, and at least 40 % of the population have access to natural gas in their homes. To construct a similar hydrogen distribution system would entail a massive infrastructural project over many years[35]. Similarly, conversion of natural gas to hydrogen requires significant infrastructural investment and is energy intensive and expensive. Compressed natural gas is a mature technology; there are 12 million natural gas vehicles (NGVs) in the world. Methane is an excellent fuel in terms of local air quality and greenhouse gas emissions. Studies suggest a reduction of 18 – 38 % and 2 – 21 % for petrol and diesel, respectively[36-38].

Hydrogen must be compressed for transport fuel use. The current standard is compression to 700 bar. This requires 13 % of the energy content of the gas[39]. In comparison, compressed natural gas (200 – 220 bar) requires of the order of 3.3 % of the energy of the gas[25]. At 700 bar the volumetric energy content of compressed hydrogen is of a similar order to CNG at 220 bar. Safety is a key concern as 700 bar is a very high pressure.

Table 5 Energy production from crop digestion. Adapted from[6].

	Maize	Fodder beet	Grass
Methane yield m^3/ha	5748	6624	4303
GJ/ha	217	250	163
Process energy demand for digestion GJ/ha	33	38	24
Energy requirement in cropping GJ/ha	17	20	17
Total energy requirement GJ/ha	50	58	41
Net energy yield GJ/ha	167	192	122
Output (GJ/ha) Input (Total Energy)	4.3	4.3	4.0

Efficiency of hydrogen production

Hydrogen produced at a power plant or wind farm must be compressed and transported. Losses between production and application are in the range of 39 to 49 % for steam reforming (20 – 30 % in steam reforming, 6 % loss in pipelines, 13 % in compression) and 49 – 53 % for electrolysis (26 % in electrolyzing, 4 – 8 % loss in grid transmission, 6 % loss in pipelines, 13 % in compression)[40]. According to Bossel[41] for each 100 kW_eh of electricity, the net energy used by an EV will be 69 kW_eh, while that of a fuel cell vehicle operating on hydrogen will be 23 kW_eh.

Biogas and biomethane

Biogas or biomethane can be produced from a range of feed stocks such as organic waste materials (Fig. 3a) and crops including those not used directly for human consumption. Marginal land and land unsuitable for food production can be used. The feedstock is digested in a sealed vessel. The produced biogas is scrubbed and upgraded to 97 % plus methane, which may be discharged to the gas grid (Fig. 3b) or injected directly into a NGV vehicle[25] (Fig. 3c). Table 2 highlights the sustainability of compressed biomethane from municipal solid waste (MSW). Singh and co-workers[42] highlighted that waste resources can typically allow for 2 % of the energy in transport through digestion of slaughter waste, slurries, and MSW. These are all highly sustainable biofuel systems. To achieve more than 2 % of the transport fuel market, biomethane must be produced from agricultural crops. With reference to Table 5 (and comparison to Fig. 2) it may be noted that the energy balances are far superior to first generation liquid biofuels. A simple calculation highlights the potential of this technology. Allowing for an average net energy yield of 120 GJ per hectare per year produced on 20 % of all arable and pasture land (7.6 × 10^6 km^2 or 7.6 × 10^8 ha) the potential production is 91.2 EJ; this is almost equivalent to the world's TFC in transport (95 EJ) in 2008[6].

Algae are considered to be the holy grail of biofuels. The energy balance (and associated cost) is significantly affected by the dilute nature of micro algae and the requirement to dry the algae to allow esterification of the lipids. It is suggested that biomethane is preferable to liquid biofuel generated from micro algae as the process does not require drying[43,44]. Marine algae (or macro algae) may be very suited to multi-feedstock anaerobic digesters in coastal areas. Biomethane may be the optimal vector for energy from algae.

Conclusions

This paper, in its brevity, can not deal with every aspect of renewable transport energy but has the ambition of assessing the big questions. Electrification of all transport is unlikely due to the scale of energy in transport but should be a big part of the solution, as it allows for storage of variable night time electricity. First generation liquid biofuels do not optimize energy return per unit of land in the form of transport biofuel, will struggle with sustainability issues, and will only ever account for less than 10 % of the energy in transport. Second generation liquid biofuels need a cheap abundant source of lignocellulosic feedstock. EVs are more efficient than hydrogen fuelled vehicles when the hydrogen is sourced from electrolysis. Methane is always cheaper than hydrogen and biomethane has a superior energy balance to first generation liquid biofuels. Transport fuels of the future will require numerous sources; there is no silver bullet. Detailed research in biofuel materials and technologies are required to optimize the resources of all renewable transport systems. mt

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