



Future fuels

Could Audi's investment in drop-in fuel technology prove to be the game-changing next leap forward for transport worldwide?

For those not involved or enthusiastic about motor sport,

it may appear to be a waste of time, money and resources. The apparent excessive consumption of limited fossil fuels and the emission of CO₂ into the atmosphere in the pursuit of speed, pleasure, entertainment and profit render motor sport vulnerable to criticism from environmentalists and indeed from vote-seeking governments.

The same criticisms are aimed at motorists, though to a lesser extent, as even environmentalists have a need to get about. While

BY PETER WRIGHT

governments are attempting to address the problems of potential fossil fuel shortages and climate change, by putting pressure on automobile manufacturers and at the same time encouraging alternatives to the petrol and diesel engine, they are losing the battle as developing

nations crave for, and achieve, personal mobility. Mainstream motor sport has tried to stay relevant by introducing KERS to

Formula 1 hybrids to use plants and - from 2014 - putting the emphasis on fuel efficiency in both categories. The FIA, encouraged by governments in Europe, is introducing city racing with all-electric vehicles in Formula E, though how the electrical energy for these will be generated remains to be determined.

Now, however, a technical solution with potential is at hand. And it's a solution not just offering potential for carbon-neutral, guilt-free motorsport, but also carbon-neutral, guilt-free motoring, and indeed all forms of

transport. Courtesy of Audi and their synthetic biology engineering partners, Joule Fuels, this is not merely a scientist's dream, demonstrated at the molecular level on the laboratory bench. Already it is way beyond that, with pilot production under way in the desert of New Mexico, with a predicted commercial production of drop-in, carbon-neutral fuels in the second half of this decade.

As is well known, all fossil fuels, including oil, are the product of sunlight, CO₂ and water, converted by a variety of biological organisms, heat and pressure into

hydrocarbon fuels over a period of several million years. Fossil fuels are the energy of the sun captured in chemical form as a solid in the form of coal, as a liquid in the form of oil, and as a gas in the form of methane or natural gas. Since mankind discovered the value of readily available energy deposits over 250 years ago, and unravelled the science behind their formation, it has been clear that using new biological processes to shortcut the production of fuels would be highly desirable. The last 30 years have seen ever more rapid progress in the development of the techniques required to do this and the evolution of the science of synthetic biology, the design and construction of biological devices and systems for useful purposes.

Flagship Ventures has been at the forefront of this initiative since 2000, providing finance for the conception, launch and realisation of novel technologies and processes outside of typical constraints, resulting in the formation of companies several

years before more mainstream investors spotted that an emerging market opportunity is likely to become compelling.

The majority of the effort to produce renewable fuels has been based on two main approaches:

- The sun's energy and CO₂ are captured by plants, which are harvested to produce sugars. Fermentation or other biological processes are used to turn these sugars into fuels, or something that can be turned into fuel - eg ethanol, and more recently diesel.
- Algal biofuels also capture the sun's energy and CO₂ and accumulate lipids in their cells. After harvesting and processing, the lipids are converted into biodiesel or kerosene (jet fuel).

To be successful, the products of these processes must not only be relevant to society's needs, but must

be producible below market prices for competing oil-based products. Many of these processes have so far proved to be uneconomical on the basis of their competition with food energy return on energy invested, and the costs of post-processing and scaling up.

In 2009, a new approach emerged, pioneered by Joule BioTechnologies - now Joule Unlimited. The company was founded by Nour Alkay and David Berry, partners in Flagship Ventures, and funded privately so that the control of information could be maintained. Joule has developed a range of patented bio-organisms that streamline the process of capturing the sun's energy and CO₂ and that directly synthesise and secrete specifically designed hydrocarbon end products. No sugars or biomass are needed in the process. While algal biofuels attempt to do this, they required batch processing and suffer from efficiency limitations due to the accumulation of the desired product in the organism

and the associated separation and post-processing costs. Joule's process shortcuts the synthesis of hydrocarbons into a single, continuous, biological step. One way of looking at it is that Joule is making dairy cows, rather than bulls for the beef market - they're milking the organism, rather than slaughtering it.

Joule Unlimited set out to develop this one-step process with specific objectives:

- It must not deplete or compete with agricultural land.
- It must not require fresh water, nor compete with human and agricultural demands for water.
- It must produce 'drop-in' products that are compatible with existing infrastructures.
- It must have a cost structure that would, without subsidies but including capital costs, be lower than fossil-based equivalents.

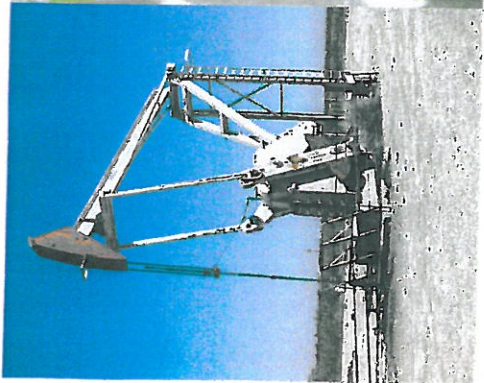


product in the organism

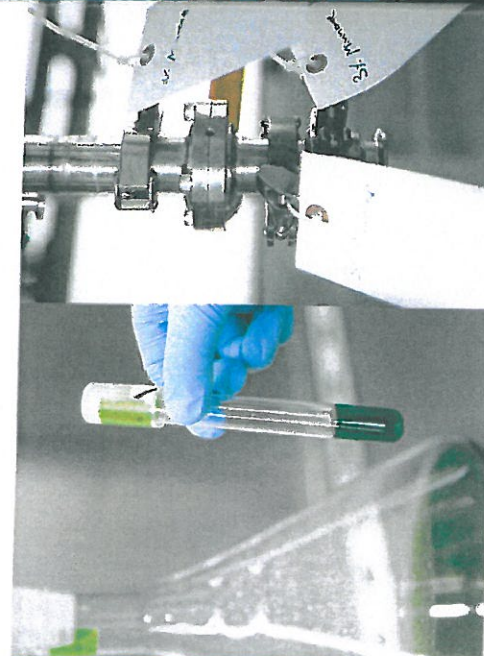
This is potentially the most significant automotive, aviation and shipping technology since piston and turbine IC engines

Joule's drop-in fuel doesn't require agricultural land, and won't be competing for space with food - instead they use the desert





The old oil pumps of New Mexico (above) could be replaced by cyanobacteria (pictured centre), which could soon be producing renewable fuels on a large scale



reproduction to the required culture density, an internal biological switch is triggered to stop growth and hence solar energy is deployed in a further eight weeks, all the product synthesis, which is secreted as 'waste' from the cells, and none is wasted on growth and reproduction. At the end of these eight weeks, the organisms are collected and burned, with the heat generated being used within the overall process, and a new culture initiated.

Secondly, the cells are engineered to produce specific products, selected to be interchangeable with industrially used, oil-based products. Products are either volatile or organic, and the range of hydrocarbons and the range of hydrocarbons Joule states that it will be able to make reads like a fuel formulator's chemistry set. Indeed, Joule has reported making a wide variety of hydrocarbons, with carbon chains from 2 to 34 carbon atoms in length. Volatile products such as ethanol are passively released

from the cells, and are collected as a vapour using the sun's energy. Aqueous products, such as diesel, require the bio-engineering of a transporter for secretion and are then captured by centrifugal separation.

Finally, the engineering of their SolarConverter - using low-cost materials with proven, long outdoor lifespans and capable of passive thermal management - is a key technology. The 'soup' - water, cyanobacteria and gaseous CO₂ - is kept below 50degC, but not allowed to drop to too low a temperature at night to ensure that the organisms function as desired.

Audi's plan is that for every litre of fuel a customer puts into the tank, they'll put a litre of e-fuel into the network

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- They do not require biomass and agricultural land, and are not competing with food. They use desert.
- The primary energy input is sunlight, the most plentiful energy source on Earth.
- Waste CO₂ from power, steel and cement plants is used as the source of carbon.
- The water used in the process can be brackish and non-potable, so there is no competition with human or agricultural needs.
- There are virtually no waste products.
- The fuels produced are cost-competitive with existing, oil-based fuels.

The numbers quoted by Joule similarly indicate that there are no limitations on production. They claim that to produce all the transport fuels used by the USA would require just 5 per cent of the desert land area in the USA.

- Joule are currently producing Sunflow-E at 75,000/ha
- The target for Sunflow-E is 230,000/ha
- The target for Sunflow-D is 140,000/ha
- Algae yield diesel at 20,000/ha
- Corn based ethanol yields 4,000/ha

They further claim that to produce all the world's transport fuel requirements would require the CO₂ from just the existing steel and cement plants. It is massively unlikely that mankind will cease to use steel and cement. Similarly, there are massive, brackish water aquifers, not currently usable. Perhaps most pertinently however, at current and foreseeable oil prices, the products are cost-competitive without subsidies.

Too good to be true? Audi does not think so. Some years ago, Audi recognised that the eventual electrification of cars would require massive R&D, production facilities and infrastructure investment. Whether EVs would be powered by on-board battery storage or hydrogen fuel cells, Audi's investment in the internal combustion (IC) engine and their superb range of gasoline and diesel engines would become obsolete. Audi foresees this starting to happen from as early as 2020, and decided that it needed to act. Their head of sustainable product development, Reiner

Joule claim that just 5 per cent of desert land in the USA would be needed to meet all the transport fuel needs of the entire country



Mangold, provided some insight into the company's vision.

When the company realised that it had to do something to maintain its investment in IC engines, he explained that it set out to analyse the life-cycle carbon emissions of current and future cars. Audi believes that EVs will be needed for transport in cities, and plug-in hybrids will have a place as dual-role cars for city and general use, but they will still require IC engines. 80 per cent of the life-cycle carbon emitted by a car comes from the fuel consumed, the rest comes from making the car and the fuel. Their analysis showed that the carbon emitted during the life of a renewable-electric powered EV could be bettered if a conventional IC-engine car used a carbon-neutral, synthetic fuel.

The added advantage of this solution is that the technology, production plants and infrastructure required already exists, provided the synthetic fuels truly are drop-in. Once Audi's engineers had made this analysis, they knew exactly what they were looking for. Scouring the world for carbon-neutral

substitutes for fossil fuels, they identified two potentially viable technologies, and have bet on - and invested in - both.

The first is e-gas. The process technology, developed by Stuttgart-based SolarFuel, converts surplus wind power electricity - of which there is plenty in northern Germany - into hydrogen by electrolysis. Methanation further converts the hydrogen into gas by combining it with waste CO₂ from biogas plants, which are also plentiful in Germany. The gas is fed into the existing network, effectively providing an energy storage system for the excess wind power - a very politically popular development. Audi and SolarFuels have built a pilot plant in north-east Germany.

The second is e-ethanol and e-diesel, as Audi has named Joule Unlimited's synthetic biofuels. In 2011, Audi together with Joule Unlimited, formed Joule Fuels, and the relationship means that while Joule has secured its technology with patents, Audi has exclusive automotive rights to these and future automotive fuels. These fuels are sulphur-free, and the diesel are a high

Audi's first demonstration facility for e-fuels in the New Mexico desert. They've also partnered SolarFuel to build an e-gas pilot plant in Germany



cetane number, indicating good burning properties. Audi brings technical support to the fuel development process, in the form of know-how and hardware in the field of fuel and engine testing. Gaining exclusivity may appear a surprising achievement, but Audi says that when it approached Joule in 2011, there was no sign of interest from the US automotive industry. Audi is very conservative with the figures it uses for production economics, upon which its business plan for these fuels is based, and it is the business plan that is one of the most intriguing aspects of Audi's vision.

Audi do not want to become fuel manufacturers or distributors, but they do want to encourage the production of e-fuels at an economic price, and to see them added to the fuel distribution networks around the world. They also want Audi customers to continue to be able to buy IC-engined cars that have the lowest life-cycle carbon emissions, at least equal to an EV's. To achieve this, they plan to provide purchasers with an agreement that for each litre of fuel put in the tank, Audi will put a litre of e-fuel into the network, so that they effectively run solely on carbon-neutral fuel. This model is the same as for purchasers of renewable electricity: they do not need a new set of (green) wires connected to their house, attached to a wind turbine, they simply sign a contract with a renewable electricity supplier. Indeed, any EV owner who wishes to be truly



(Top) The bacteria and their output are analysed in the Hobbs laboratories. **(Above)** Paul Snaith from Joule shows Reiner Mangold, Audi's head of sustainable product development, the first cultures

carbon-neutral must do just this for all sources of electricity they use to recharge their car. Audi offer this for its range of natural gas engines using Audi e-gas, and initially for its diesels and eventually gasoline-powered cars, whatever the fuel mix of gasoline and ethanol. The key marketing feature is that this form of certified, guilt-free motoring will be exclusive to Audi owners, as per their exclusive automotive rights contract with Joule Fuels.

Not many silver bullets actually work, but if Joule and Audi's vision comes to fruition - and it is the economics of production

relative to oil-based fuels that will determine this - and synthetic fuel production reaches significant scales, this technology is a true game-changer. It's potentially the most significant automotive, aviation and shipping technology since piston and turbine IC engines were invented. It is applicable not only to new vehicles and aircraft, but also to all existing ones, solving the transport industry's CO2 problem at a stroke. No new engine technology is needed, though improvements to efficiency, providing they are cost-effective, will always be required, and there would be no call for

new infrastructure. Automobile manufacturers' full range of cars, large and small, will meet the EU CO2 emission standards by a mile, and Audi will be the first to be able to claim this, therefore avoiding the EU's fines. Energy supplies will no longer be subject to the geopolitics that drive so much of the conflict in the world. There will be no need to exploit potentially environmentally risky and costly sources of oil such as deep-water, the Arctic, Canadian tar sands and shale. These unconventional sources of oil are mostly uneconomic at an oil price below \$70-90/barrel. Indeed, one can anticipate the biggest problem for synthetic fuel will be resistance by Big Oil...

This may all be a long way off, but Joule and Audi are demonstrating that producing carbon-neutral transport fuel is possible. Now they must demonstrate that the extremely favourable-looking economics work. With such a promising start, there appears to be a very high chance that synthetic biology will succeed in solving the transport industry's CO2 problem, and ease the pressure on oil supply. The impact on all forms of mobility could be far, far reaching.

The CO2 emitted by raccars on the track is a small percentage of the total CO2 emitted by motorsport. By far the majority comes from the transport, particularly flying, of equipment, personnel and fans around the world. In the latter case, motorsport is no different from football, the Olympics, and rock concerts. However, environmental discussions tend to veer towards the emotional, and the sight and sound of 20-30 cars, each with more power than most people will experience in a lifetime, going round and round at full power is how motorsport's environmental credentials tend to be judged. It will take several years before the transport emissions can possibly become carbon-neutral, but there is a real, near-term opportunity to not only achieve carbon neutrality on-track, but also to pave the way for public acceptance of synthetic fuels and to encourage car buyers to take up what Audi plans to offer its customers: guilt-free motoring.

The ultimate Garage 56? 

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