Why Physics Should Decide the Future of Transport

The hunt for a commercially viable, hugely scalable and environmentally friendly alternative to fossil fuels is in full swing. However, for such an incredibly important project, the hunt seems far too haphazard, with a slavish subservience to what the current state of the world permits. The vital thing is not to be blinkered by what is economically viable now, but to look instead at what physics has to say about the various alternatives. I argue that nowhere is this truer than in determining what will power our transport in the future.

To demonstrate this let’s look at two leading and totally opposed routes of powering our transport in the future. The first is one of the world’s most successful and established alternative energy sectors – producing biofuels in Brazil to fuel an internal combustion engine fleet. The second is one of the most ambitious, but under-developed alternatives - producing electricity from vast concentrated solar power (CSP) plants in the Sahara to power an electric engine fleet.

The first step in investigating which should be the future alternative is to look at these on a very fundamental level – the basic energy flows. The ‘electrical’ alternative’s energy flow is simple; solar energy from the sun is converted into electric energy in the Sahara before being transformed into the kinetic energy of our cars. The biofuels alternative is slightly more complicated. The end result is obviously the same – we want kinetic energy. What is the overall energy flow though?

Consider the lifecycle of the most successful and widely used biofuel, ethanol:

Plants capture light from the sun to create glucose by photosynthesis:

\[ 6\text{CO}_2 + 6\text{H}_2\text{O} \overset{\text{Light}}{\rightarrow} \text{C}_6\text{H}_{12}\text{O}_6 + 6\text{O}_2 \]

During the ethanol fermentation, glucose is decomposed into ethanol and carbon dioxide:

\[ \text{C}_6\text{H}_{12}\text{O}_6 \overset{\text{Heat}}{\rightarrow} 2\text{C}_2\text{H}_5\text{OH} + 2\text{CO}_2 \]

During combustion in a car’s engine, ethanol reacts with oxygen to produce carbon dioxide, water and heat:

\[ 2\text{C}_2\text{H}_5\text{OH} + 6\text{O}_2 \overset{\text{Heat}}{\rightarrow} 4\text{CO}_2 + 6\text{H}_2\text{O} \]

Adding all three reactions together we find equal numbers of each molecule on either side of the equation and so the net reaction for the overall production and consumption of ethanol is simply:

\[ \text{Light} \rightarrow \text{Heat} \]
So biofuels are just another form of solar power! Light energy absorbed by plants is transformed into heat energy when the biofuel is burnt. In a car, this heat energy is of course converted into kinetic energy by the internal combustion engine.

This makes comparing the two alternatives wonderfully simple. All we’re doing is looking at two ways of converting solar energy from the sun into kinetic energy for our transport needs. Moreover, the numbers used to compare these two options are not wild projections – while at very different stages of commercial development, the relevant technology for each option is largely in place. These two important commonalities mean that the result of the following comparison is very significant.

Let’s start with ethanol. There are several points in the production of ethanol that lead to energy losses. In the chemical equations we can see there are two: photosynthesis and fermentation. These are coupled with the energy inputs needed for cultivation like tractors, irrigation, fertilizers, etc. However, the most significant energy loss occurs right at the start with photosynthesis; when plants convert solar energy into chemical energy in the glucose (or other carbohydrate). The most efficient plants are just 2% efficient at storing energy from the sun as chemical energy. This is incredibly low. Remember, this is before the energy losses from fermentation are counted out, let alone the additional energy inputs required in terms of farming and processing.

This poor efficiency is borne out by the real world numbers. The best in class ethanol plants in Brazil produce 80 tonnes of sugarcane per hectare which is then processed into 17600 litres of ethanol. Bioethanol has an energy density of 6 kWh per litre. So:

- That’s (17600 x 6000) = 1.056 x 10^8 Wh/ha/year
- Which is (1.056 x 10^8/365/24) = 1.2 x 10^4 W/ha
- Or simply 1.2 W/m²

Let’s compare this number to the solar power each square meter in Brazil receives from the sun. The average raw power of sunshine per square metre of flat ground where sugar cane is grown is roughly 200W/m². This gives an overall efficiency of only 0.6%!

Let’s compare this with the second alternative. Concentrating solar power works by concentrating the sun’s rays onto a liquid. The liquid then heats up, and can be used to boil water, which then forces it way through a steam turbine, generating electricity. The best established form of CSP uses long parabolic troughs covered with reflective material to concentrate the sun’s power on to a thin tube called a receiver, in the centre of the parabola.

This technology is used at a new, large project near Granada in Spain called Andasol. Thermal energy produced during the day will be stored in liquid salt tanks for up to seven hours, allowing a continuous and stable supply of electric power to the grid. The power station is predicted to produce 350GWh per year from parabolic troughs occupying 400 ha. So the Andasol project will deliver:

- An average power of (350 x 10^9/365/24) = 4.0 x 10^7 W or 40MW
- Which on 400ha will give \( (40 \times 10^6/400) = 100,000 \text{W/ha} \)
- Or simply 10W/m\(^2\)

In Spain the average raw power of sunshine per square metre of flat ground is about 180W/m\(^2\). This gives an overall efficiency of 5.6%, an order of magnitude greater than ethanol production! Of course the idea is that these CSP plants would be located on a vast scale in the Sahara and the electricity would have to be transmitted to Europe and the rest of Africa. Power would then be lost in transmitting over the large distances required, although surprisingly little when high-voltage direct-current (HVDC) transmission lines are used. The power losses on a 3500km-long HVDC line delivering electricity from the Sahara to a city in Europe or Africa, including conversion from AC to DC and back, would be about 15%. Given that ethanol also needs to be trucked or piped to ports for export and then shipped across the world, CSP will still deliver far greater power per square metre than the most efficient ethanol plants today. CSP is simply far more efficient at converting energy from the sun than biofuels.

Now let’s see what physics has to say about how efficient each of these two routes is at transforming energy delivered to their respective engines into kinetic energy.

How much of the chemical energy stored in ethanol is converted to kinetic energy by an internal combustion engine? A century of improvements hides a surprising answer – only about 25% of the energy in ethanol (or petrol) actually gets to the wheels of a car. Over three-quarters is wasted as heat, mostly from the exhaust or through the cooling system. Most internal combustion engines use the Otto-cycle to turn heat from combusting fuel into useful work. Why is this efficiency so low and could it be significantly improved?

Let’s look at the physics of the Otto-cycle. The maximum theoretical thermal efficiency of the Otto cycle is:

\[
\eta = 1 - \frac{1}{r(1 - \gamma)}
\]

Where \( \eta \) is the efficiency, \( r \) is the engine’s compression ratio and \( \gamma \) is the heat capacity ratio for the fuel. The engine’s compression ratio is simply how much the fuel is compressed before it is ignited. For any fuel, \( \gamma \) is some fixed constant greater than 1 so efficiency increases as you increase the compression ratio. However, there is a fairly rigid boundary to how much you can compress a particular fuel. As you increase the compression you also increase the risk of ‘knocking’ – extremely rapid and spontaneous combustion which occurs before the fuel is sparked, massively reducing the effectiveness of the engine. This is what an octane rating indicates; fuels with high octane ratings are less prone to knocking. Ethanol has an octane number of 89, fairly similar to gasoline and so has a similar limit to how much it can be compressed. The absolute theoretical efficiency of combusting ethanol in an Otto-engine is thus very similar to gasoline’s – about 0.6 (60%). The laws of physics do not permit any higher efficiency.

In practice it is actually very difficult to get anywhere near this. This theoretical thermodynamic limit assumes that the engine is operating in ideal conditions: a frictionless world, ideal gases, perfect
insulators, and operation at infinite time. The real world is substantially more complex and all the complexities reduce the efficiency.

This compares very poorly with the efficiency of an electric car. Electric motors are much more efficient in converting stored energy into driving a vehicle and efficiencies of 90-95% are currently achieved. For cars on the road the amount of electrical energy converted into useful kinetic energy drops to about 80%, still well above the 20-25% achieved by petrol cars.

So, the physics seems pretty unequivocal on which route is more efficient. First, CSP captures the sun’s power at about 5% efficiency whereas producing ethanol retains just 0.6%. Second, electric engines have an efficiency of 90% whereas an internal combustion engine using ethanol has an absolute limit of 60% with some very challenging real world obstacles to coming anywhere near half that.

While the physics might be clear on which route to pursue, we have to ask at this stage - is it economically realistic? CSP certainly is. All the technology it needs is ready to go. Much of the cost of CSP is in the manufacture of the parabolic troughs which focus the sun’s rays. Getting the costs down is a manufacturing challenge not a technological challenge as the Andasol project demonstrates. The high-voltage direct-current cables that would be needed are already used to transmit electricity over 1000-km distances in South Africa, China, America, Canada, Brazil, and Congo. Another hugely significant point in CSP’s favour over biofuels is that it doesn’t use valuable cropland. In fact it seems like a particularly elegant use of the last areas of land that we don’t really utilize - deserts.

How about electric cars? Admittedly we are further off but certainly not out of sight. The main stumbling block is the batteries that store and supply energy to the engine while on the move. They need to improve in range and price. The Tesla Roadster has 450kg of lithium-ion batteries giving it a range of 354 km. This is pretty good - only 8.3% of UK commuters travel more than 30 km to their workplace. If this range is combined with recharging stations situated on major routes like petrol stations then we can keep all the independence and simplicity that solo travel gives you. Unfortunately the Tesla Roadster has a price tag of £100,000, not obscene for a ‘muscle car’ but no good at all if electric cars are to replace petrol ones. The price of batteries has come a long way since the early lead-acid versions, and with 9.5 million tons of lithium in ore deposits and thousands of times that in the sea, it doesn’t seem unrealistic to see prices dropping still further.

This is all incredibly exciting. One of our most successful examples of alternative energy at the moment is the production and use of ethanol in Brazil. After 30 years of sustained state investment and support at every level, the ethanol business there is now a multi-billion dollar industry, existing without subsidies. Last year 50% of petrol sold in Brazil was ethanol and its price is still dropping. And we’ve just seen that this is one of the most inefficient forms of alternative energy! Similar levels of commitment to concentrated solar power and electric cars would give a form of energy and transport that would blow biofuels, and definitely fossil fuels, out of the market.