Hydrogen

A CO_2-free fuel?

The concerns about global warming and greenhouse effect have, quite justifiably, fuelled the search for 'carbon-free' energy sources to curb CO_2 emissions. Road transport is a major user of energy and virtually all of it is based on relatively 'carbon-intensive' fossil fuels. It is therefore the subject of much attention as more 'greenhouse-friendly' alternatives are being considered. Using hydrogen is heralded as such an alternative, with visions of the world gradually converting to the 'hydrogen economy'.

The greenhouse effect is a truly global i.e. worldwide issue and the location where greenhouse gases (GHG) emissions occur is immaterial. The analysis of the impact of any measure, event etc. on the GHG balance must therefore also be truly global if it is to serve a purpose and have credibility.

Pure hydrogen is the cleanest of fuels, as it obviously contains no carbon and produces only water when burned. In addition pure hydrogen can be fed to fuel cells, which are considerably more energy-efficient than internal combustion engines. With regard to conventional hydrocarbon-based fuels, a higher hydrogen content is regarded as 'CO_2-friendly' as, besides containing less carbon, the fuel also has a higher heating value per unit of mass.

Hydrogen, however, is not a primary energy source but rather an energy carrier. Indeed it does not occur as such in nature and has therefore to be manufactured from something else. In its natural state, hydrogen is usually to be found bound with oxygen in water or with carbon in hydrocarbons. Releasing molecular hydrogen requires breaking these (very stable) bonds and is therefore an energy-intensive process. In practice this is done either by partial oxidation or steam reforming of light hydrocarbons, or by electrolysis of water. In the former case, the bulk of the energy required is hydrocarbon-based. In the latter case, the primary energy source used to produce the electricity has to be considered.

The overall picture only emerges when the complete cycle is considered in a so-called 'cradle-to-grave' or, as appropriate for fossil-based road fuels, 'well-to-wheels' analysis. Many well-to-wheels pathways have been proposed and are being actively studied in order to make hydrogen a truly attractive alternative. Amongst them the combination of hydrogen production from natural gas associated to fuel cell vehicles appears to be the most promising even though many technical challenges remain.

The purpose of this article is not to deny the potential of hydrogen as a future fuel but rather to highlight the pitfalls of a superficial analysis and to illustrate how it can lead to the wrong conclusions. In the following lines we consider two situations where the apparent CO_2 emission reduction may be turned into an increase when looking at the complete well-to-wheels balance.

THE C/H MIRAGE: THERE IS NO SUCH A THING AS A FREE LUNCH!

Hydrocarbons, essentially in the form of crude oil, come as a cocktail of molecules, both saturated and unsaturated. Generally there is not enough light material in the native crudes to meet demand, so heavy molecules have to be cracked into smaller unsaturated ones. Starting from a given hydrocarbon source, decreasing the C/H ratio of the fuel pool therefore requires hydrogen to be added. Although some of the energy required for doing so is recovered in the form of increased energy content of the fuel, the global energy balance is invariably negative because of practical and thermodynamic limitations of heat recovery.

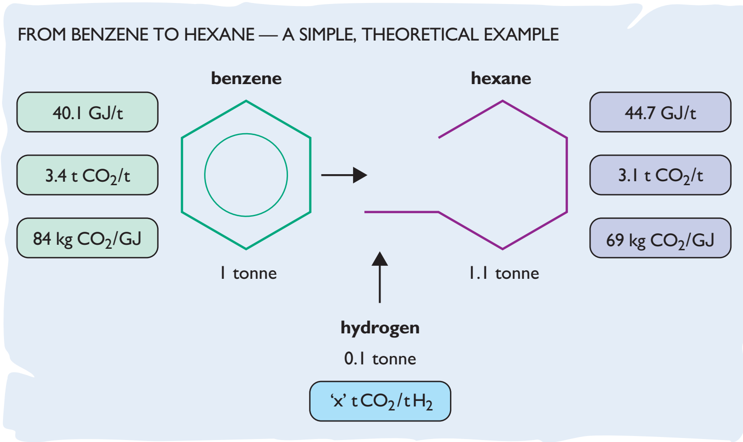


Figure 1
From benzene to hexane (heating values from Phillips databook)

The net result is that adding hydrogen to a fuel for the sole purpose of increasing its heat content is always a net CO_2-producing endeavour. This can be illustrated by a simple, if somewhat theoretical and extreme example. Let us consider benzene and its fully saturated equivalent hexane. The relevant data is shown in Figure 1.

On a 'CO_2-friendliness' basis hexane would obviously always be preferred to benzene as a fuel. However, if only benzene was available in the first place, hexane would need to be made. Turning 1 tonne of benzene into hexane requires approximately 0.1 tonne of hydrogen. Manufacturing this hydrogen causes the release of a number of tonnes of CO_2, the actual number depending on the feedstock, the process used and its energy efficiency. The most widespread hydrogen production route is steam reforming of light paraffins, mainly methane, which typically generates between 8.5 and 9 tonnes of CO_2 per tonne of hydrogen. Processes using heavier feeds, such as partial oxidation of heavy residues or coal, generate much more, up to 15 tonnes of CO_2 per tonne of hydrogen. As we will discuss in the next section, even 'renewable' hydrogen can hide significant CO_2 emissions.

The calculation is easy to complete. About 1.1 tonnes of hexane are produced for a combined potential CO_2 emission of (3.4 * 1 + x * 0.1) per tonne of hexane. The results are shown graphically in Figure 2. Within the realistic range of CO_2 emissions from hydrogen production, the CO_2 balance is clearly always negative.

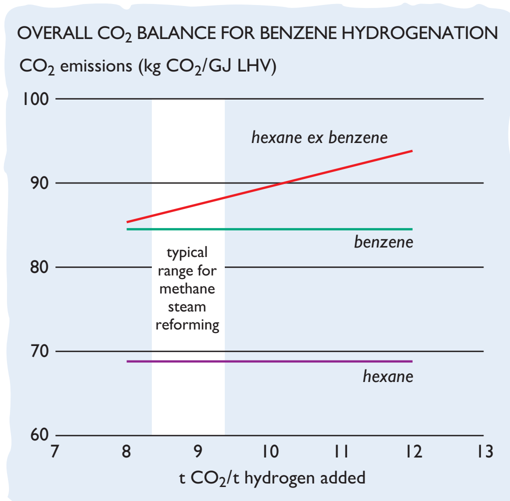


Figure 2
CO_2 emissions in benzene hydrogenation: these can only be justified if they are more than compensated for by the increase in fuel efficiency.

As a more practical example, we have estimated that adding 0.8% m/m of hydrogen to diesel[1] would result in a net increase of about 2% of the CO_2 emissions associated with this fuel (assuming hydrogen is made with natural gas). With a forecasted diesel demand well in excess of 150 Mt/a in the EU, this would correspond to some 10 Mt/a of additional CO_2 or 10% of the current total emissions from EU refineries. It also has to be said that this level of hydrogenation requires dedicated plants, very few of which exist at the moment.

Clearly such increases of CO_2 emissions can only be justified if they are more than compensated by genuine increases in fuel efficiency. This is normally only the case when the envisaged fuel quality change enables a novel, fuel-efficient engine technology to emerge. In the case of diesel, efficiency gains are unlikely to materialize as a result of changes in fuel quality, so the cost of such changes, both in financial and in CO_2 terms, may be an inevitable corollary to achieving the desired targets for air pollutant emissions.

[1] *This is roughly the amount of hydrogen that would be required to saturate the bulk of the aromatics in diesel*

HOW ‘RENEWABLE’ CAN HYDROGEN BE?

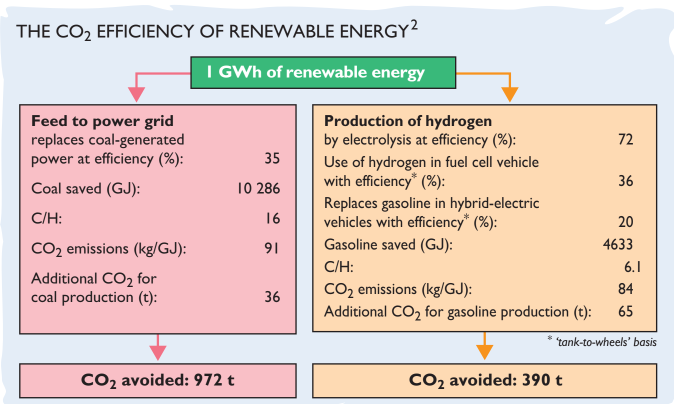
Many well-to-wheels analyses compare an existing situation, or a future situation based on a ‘do-nothing’ or ‘business-as-usual’ scenario, with an alternative view for the future involving novel technologies, mode shifts etc. In most cases, the envisaged changes are gradual and partial, as evolution is generally more likely than revolution. As the changes are marginal, so are the effects. Average values are therefore rarely usable.

Production of hydrogen by electrolysis immediately raises the question of the source of electricity. Enthusiasts will mention renewable energy such as wind or hydropower, raising the prospect of CO_2-free hydrogen. Reality is, however, likely to be somewhat different.

Electricity generation accounts for the largest share of the energy consumed worldwide, and demand for electricity as such is increasing. There certainly are prospects for generating increasing amounts of electricity from renewable sources, but a large part of the balance will continue to be supplied by fossil fuels (coal and gas essentially) for a number of decades to come. As renewable sources (as well as nuclear energy) are most likely to be favoured (on the basis of low variable costs or through political will) they will probably provide the base load (even in off-peak periods). Any additional electricity required to produce hydrogen would therefore effectively be generated by the marginal, least efficient plants. In many parts of the world this means coal-fired power plants.

From a global point of view, hydrogen would therefore be effectively produced from coal, through the rather inefficient process of electricity production followed by electrolysis of water. The only exception to this would be production of hydrogen in remote areas with a dedicated renewable power plant (e.g. solar) that could not practically be connected to a power grid. As transport and storage is one of the major problems associated with hydrogen, this is unlikely to occur on a large scale.

Figure 3
Using electricity from renewable sources to replace coal-based electricity is more CO_2-efficient than using it to produce hydrogen for use as an alternative road fuel.



Independently of economic considerations, and from a pure CO_2 balance point of view, one would wish to select the most CO_2-efficient way to make use of the limited amount of renewable electricity. Figure 3 provides a comparison of two possible routes.

1 GWh of renewable electricity may be used as such through the common grid. It will then displace the same amount of marginal electricity, likely to be coal-based. Alternatively it can be used to produce ‘renewable’ hydrogen by electrolysis. Assuming we are in the future, say 2015, this hydrogen is used in efficient fuel cell vehicles. This displaces other fuels such as gasoline, by then somewhat more efficiently used than today in hybrid-electric vehicles. The balance clearly shows that replacing coal-based electricity is much more CO_2-efficient than producing hydrogen to be used as alternative road fuel. The production of ‘renewable’ hydrogen effectively results in an almost three-fold global decrease of the CO_2-effectiveness of the renewable energy.

The ratio of CO_2 avoided between the two options is of course heavily affected by the assumptions. The same calculation for marginal electricity based on natural gas still shows a 25% increase of CO_2 avoided compared to the hydrogen route.

[2] *Electrolysis and vehicle efficiency figures from ‘Well-to-Wheels Energy Use and Greenhouse Gas Emissions of Advanced fuel/Vehicle Systems’. General Motors Corporation, Argonne National Laboratory, BP, Exxonmobil, Shell*