Evaluating energy pathways: from well to wheels

How the JEC well-to-wheels study is evolving to take account of new vehicle, fuel and biofuel options that are likely to be available in the next 10 years and beyond

Over the past decade, the JEC Research Consortium[1] has been working together to better understand the complex issues associated with future vehicles and fuels. While some of this work has involved practical vehicle testing, much of the Consortium's work has been on vehicle and fuel pathways in the European context, from a 'well-to-wheels' (WTW) perspective. Other work that is also reported in this *Review* has focused on meeting future European requirements for renewable energy and greenhouse gas (GHG) reduction through the use of biofuels in European market fuels.

The JEC WTW studies have become a benchmark reference and planning tool for evaluating energy use and GHG emissions for different conventional and alternative fuels and vehicle options. The efficient production of fuel products and their use in vehicles are both important in order to choose and invest in the best technology options to meet future EU targets. Two new reports on 'well-to-tank' (WTT) production of fuels and 'tank-to-wheels' (TTW) use in vehicles were published in 2013 on the JRC website[1]. The results from these two studies, combined into a WTW perspective, were published in March 2014 and provide an overall assessment of fuel and vehicle pathways between 2010 and 2020+.

WTW and Life Cycle Analysis (LCA) studies have, of course, been conducted for many years but the importance of these methodologies to provide a sound scientific basis for guiding decisions related to European road transport only became apparent from about 2000. Before this time, the regulatory focus was primarily on vehicle performance and exhaust emissions, and on standards for reducing road fuel sulphur levels and harmonising

[1] http://iet.jrc.ec.europa.eu/about-jec

[1] What is the JEC Consortium?

If you have heard of the 'JEC Consortium' before, it is most likely through work related to the development of the Well-to-Wheels (WTW) methodology and results. Although this is still a central part of the JEC Consortium's work, the scope of its activities has grown considerably over the years.

In 2000, Concawe recognised the importance of joining forces with the European Council for Automotive R&D (EUCAR) and the Joint Research Centre (JRC) of the European Commission on topics of common interest. The 'JEC Consortium' formed by these three partners was designed to pursue scientific and technical studies and provide factual information in evolving areas of road transport. A Scientific Advisory Board consisting of senior managers and researchers from all three organisations is responsible for agreeing on the scope of new projects, stewarding the completion of results and their dissemination to a wider audience.

The first technical area identified by the Consortium was the development of scientifically robust tools for comparing different combinations of powertrains and fuels from 'Well to Wheels' (WTW), that is, from fuel production to its consumption in vehicles. It was quickly recognised that experimental measurements could not provide all of the answers on the energy requirements and GHG emissions for new vehicle and fuel technologies; the JEC WTW approach provided a new way to fill that identified gap.

The JEC's WTW work has stood the test of time with new updates published in versions 4 and 4.a of the Well-to-Tank (WTT) and Tank-to-Wheels (TTW) Reports in 2013 and 2014 respectively, and the WTW version 4 Report in 2014. The JEC approach has also been recognised by the European Commission as a 'sound science' way to value different energy pathways and products, and was used as essential input for European legislation on renewable and alternative fuel products for energy use adopted in 2009.

Although WTW has been its most visible work product, the JEC Consortium has also pursued research in other areas. Vehicle studies have focused on evaporative emissions, fuel consumption, and regulated emissions from ethanol/petrol mixtures. More recently, the Consortium also published results of the 'JEC Biofuels Study' in 2011, a project to assess the challenges associated with achieving the 2020 targets and objectives of the EU's Renewable Energy and Fuels Quality Directives through biofuel blending and alternative fuels uptake in the European road fleet. An update of the 2011 Biofuels Study was published in 2014 and the results of this update are described in the accompanying article.

Most importantly, all of the JEC's work is published on the Joint Research Centre's website and is freely available for download, review and critique by interested researchers and organisations. The Consortium members monitor an email address (infoJEC@jrc.ec.europa.eu) for those who have questions or find technical errors in the published work that should be corrected in future revisions.

quality across European states. These developments resulted in dramatic reductions in regulated emissions from road vehicles but energy consumption and GHG emissions from road transportation continued to rise.

The objective of the JEC WTW studies has been the same since the first report in 2004: to objectively evaluate the real energy use and GHG emissions for different technology options that are important to Europe. This work has been one of continuous improvement, especially for some biofuel pathways where commercial development is still in progress and process technology options are still under development. Presenting the results and input data in a transparent way is equally important, and, in the most recent Version 4 reports, all of the input data and assumptions, together with the appropriate references, have been presented in the form of easy to use, downloadable workbooks.

The JEC study is forward looking. In broad terms, the study examines vehicle, fuel and biofuel options that are likely to be available in Europe in the next 10 years and beyond. The production of biofuels and alternative fuels is based on best available process technology. This means that the results anticipate the performance of new production plants that will be built in the future. This performance level may not be matched by existing production plants that were constructed even a few years ago.

The study also assumes a `marginal' approach, that is, it asks from what source and through what process would additional quantities of a particular road fuel, for example electricity or CNG, be produced, what equivalent quantity of conventional fuel it would displace and through what process is that 'marginal quantity of conventional fuel' currently produced.

Methodology

The performance of new vehicle and fuel options is compared to a conventional vehicle and fuel scenario. To do this, Concawe's refining model covering the European region provides a unique tool to evaluate the impact of changes in demand for conventional gasoline and diesel on marginal energy use and GHG emissions associated with fuel production. In particular, the model calculates slightly higher energy and GHG emissions for diesel fuel production compared to gasoline, reflecting the diesel quality specifications and high diesel to gasoline demand ratio in Europe.

Conventional crude oils are still plentiful, but other sources such as oil sands and shale oils are increasingly being exploited in some parts of the world. These new sources are more intensive in energy use and GHG emissions than is the production of conventional crude. While these new sources of crude products are described in the WTT Report, they are not expected to be used in significant quantities in Europe which will continue to rely on a mix of conventional crudes primarily from Europe, the Middle East, Africa and Russia. The GHG emissions associated with the production of this mix of crudes have been updated in the WTT Report using recent published information from production sites, including emissions from flaring and venting.

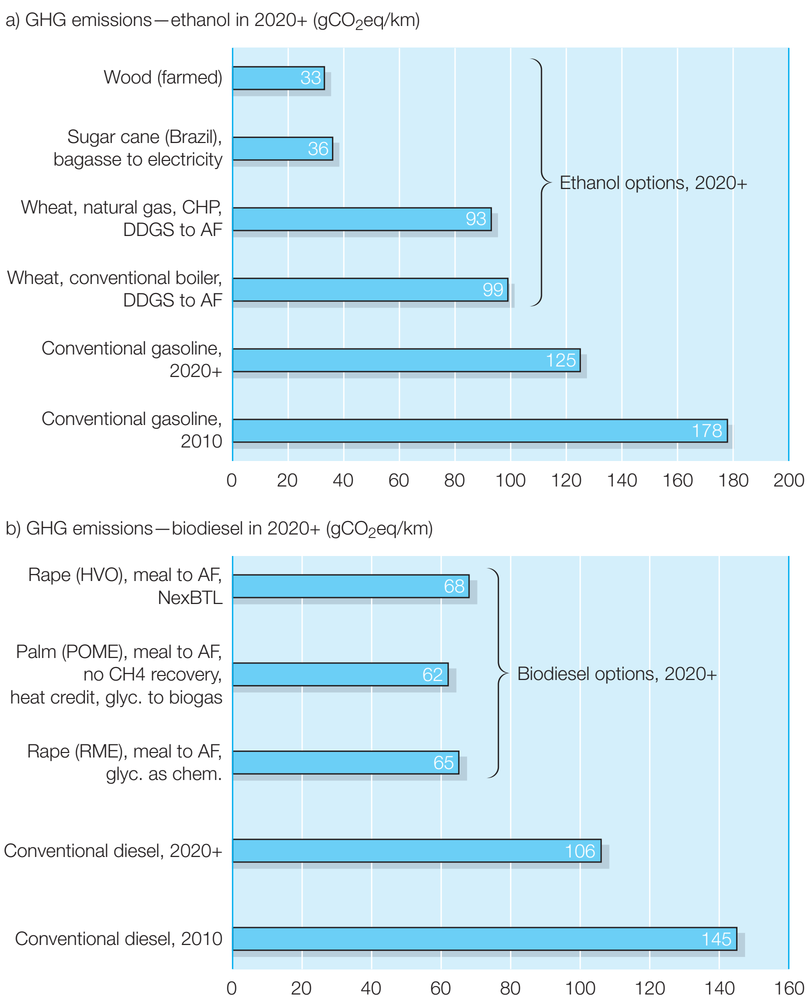
For most fuel options, a range of alternative production sources and processing methods are evaluated and described as different 'pathways'. For example, CNG may be produced from gas reaching Europe by pipeline or as LNG. Factors such as the pipeline transport distance have a big impact on the energy and GHG emissions due to pressurisation and pumping losses which depend on distance. While much of the input information would be valid anywhere in the world, scenarios are as closely tailored to the European situation as possible.

Since the first JEC WTW Study was published in 2004, the pathway emphases and priorities have evolved. In 2003, for example, much attention was given to the potential of hydrogen as a fuel for road vehicles. Hydrogen can be produced from a variety of sources, but its production is energy intensive. The first study showed that benefits only accrue if hydrogen is used in efficient fuel cell vehicles rather than in a conventional engine. While fuel cell vehicles have been demonstrated for many years, they have been slow to reach large-scale penetration in the vehicle market.

When the second study was published in 2006/7, biofuels had replaced hydrogen as the topic of interest and were quickly becoming commercially established. A major effort was put into understanding these biofuel production pathways better, including holding a workshop to obtain input from other groups and experts. Understanding of biofuels production pathways is undoubtedly much better today compared to only a few years ago, but new questions constantly arise. Biofuels remain the most challenging alternative fuel to model accurately, primarily because of the disposition and accounting of pathway co-products.

Vehicle technology has also evolved considerably since the first JEC WTW Study. The efficiency of conventional petrol and diesel engines is improving and helping to reduce the fuel needed to keep Europe moving. The baseline vehicle has been updated from a 2002 to a 2010 model year in the new TTW Study, and new vehicle types have also been modelled. For instance, plug-in hybrid and battery electric vehicles are becoming more common having the ability to recharge from street and home recharging points. This will bring electricity production into greater focus as an alternative road fuel. Considerable care has been taken in the TTW Study to compare different powertrains on a level playing field, using common performance criteria for different vehicle types to the greatest extent possible.

Figure 1 Impact of biofuels



Biofuels

Biofuels are the most challenging fuels to model, because they involve processes and co-products that extend far beyond the limits of road transportation. Current production methods for ethanol and biodiesel (FAME)[2] use only part of the cereal or oil seed, respectively, in the production process. The residue is a useful co-product that can be consumed as an animal feed or used as an energy source. Selecting between these options will ultimately be done on economic grounds, but the study provides pathways that outline the effects of these selections on energy and GHG emissions (Figure 1). Hopefully, the results also help guide those who are interested in manufacturing biofuel products with ever-increasing energy and GHG efficiency.

While some biofuels are being produced from waste, the large volumes needed to meet current and future transport demand will mostly come from purpose-grown crops. Although this is not a major energy factor in a typical pathway, the farming of energy crops does represent a major source of GHG emissions. First, fuel and GHG emissions associated with farming equipment and the manufacturing of fertilisers and other agricultural chemicals must be counted. Second, GHG emissions can also be emitted directly from the soil, and these are more difficult to estimate with precision. Much of the nitrogen in the soil is taken up by the growing crop, but some is emitted directly to the atmosphere as nitrous oxide (N_2O). Although the absolute amounts emitted are small, N_2O is a potent greenhouse gas and can have a significant impact on the overall GHG emissions from biofuel production. Experimental data show that measured N_2O emissions from individual fields can vary by up to three orders of magnitude, depending on the soil characteristics, climate, cultiva-

[2] Fatty Acid Methyl Esters

tion methods, fertilizer rates and the type of crop. Estimating these emissions is challenging and depends on detailed input information; uncertainty levels are still quite high. The new WTT Study includes an improved model to calculate N_2O emissions, developed by the JRC, to balance the need for precision with the level of input data that are available around the world.

GHG emissions are also associated with changes in land use. For example, when land is cultivated with a particular vegetation (forest, grassland or agricultural crops) for many years, the level of carbon in the soil reaches an equilibrium level which is generally higher for forest and grassland than it is for soil used for agricultural crops. After land use changes, the carbon level in the soil will gradually move to a new equilibrium, a process that takes many years or even decades. Because the first biofuels for road transport were produced from land that was already in agricultural cultivation, no significant change in GHG emissions from land use change was expected. As demand increases, however, there is increasing pressure to bring more forest or grassland into agricultural production to meet the growing need. Where this occurs, carbon will be released from the soil into the atmosphere. While the process is slow, the quantities of released GHG are significant, particularly in the case of peaty soils where large amounts of carbon are stored.

The production and demand for biofuels have now reached a point where their production has effects on a global level. Cereals, oilseeds or finished biofuels are increasingly traded on world markets. The amount of land being used for biofuel production has raised concerns that additional land may be brought into cultivation to make up shortfalls in food production. Such indirect land use change (ILUC) could also release more carbon into the atmosphere as explained above. Some argue that the improved use of already available farming land should enable food demand to be met without bringing more forest or grassland into cultivation. These ILUC effects are potentially significant for assessing the real GHG emissions impacts of biofuels but the experts agree that ILUC effects cannot be calculated with certainty today. This area remains a challenge for the future and we have not attempted to include ILUC effects in this version of the JEC Study.

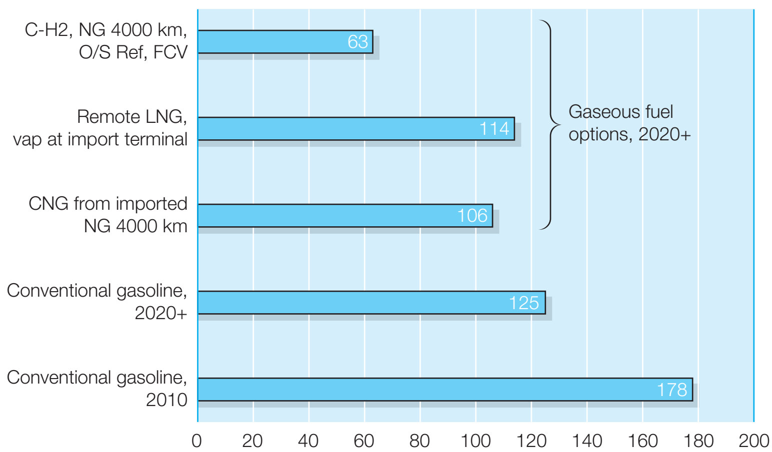
Gaseous fuels

Concerns are periodically raised about the dependence of road transport on crude oil. Liquid biofuels have an advantage that they can be blended into existing petrol and diesel and used in normal vehicles, but the fuel volume they can replace is limited by what the land can produce.

Gaseous fuels provide a possible alternative to biofuels, so their effect on overall energy use and GHG emissions is also of interest (Figure 2). Natural gas is available in very large quantities worldwide and the technology to use it in road vehicles already exists. Although the energy and GHG emission figures have changed very little since the first study, we have refined the energy needed for long distance gas pipelines in this update. We have also included an 'EU mix' natural gas case and have increased the average pipeline distance to 2,500 km which is more representative of current practice compared to the distance used in previous studies.

Based on technology and cost hurdles, the generalised use of hydrogen in road vehicles still seems to be a long way off. If hydrogen is needed in large quantities, however, it would probably be produced from natural gas, or possibly by electrolysis of water, so these production pathways have also been modelled. Hydrogen only has an overall WTW GHG emissions advantage over conventional liquid fuels when it is used in efficient fuel cell vehicles (FCVs).

Figure 2 GHG emissions—gaseous fuel options in 2020+ (gCO_2eq/km)



Electrification

The use of hybrid electric vehicle (HEV) technology has advanced steadily over the past decade and this trend is expected to continue. Hybridisation may correspond to fairly simple modifications such as stop/start systems to full hybrids where power is provided by a combination of a conventional engine and an electric motor.

Battery electric vehicles (BEVs) have also developed significantly due to improvements in battery technology, but they still struggle for public acceptance because of their limited range and high cost. An alternative development is the plug-in hybrid vehicle (PHEV). A third category is the range-extended electric vehicle (REEV) where a small conventional engine is used simply to recharge the battery.

While HEV technology improves the overall efficiency of the vehicle, the conventional engine still relies entirely on fuel on board the vehicle for its energy. BEVs, PHEVs and REEVs, in contrast, utilise electricity from the grid as their road fuel.

In this update of the TTW Study, much attention has been given to accurately model these new developments, and BEVs, PHEVs and REEVs, all using lithium-ion batteries, are included for the first time.

This increased attention on electricity is also reflected in the WTT report. The 'EU mix' figures for electricity generation have been updated with the help of JRC experts. In addition to different pathways for producing electricity from coal, gas and nuclear in best available technology power plants, an estimate has also been made of the average GHG emissions from today's 'EU mix' electricity based on national statistics.

An alternative use of electricity for road transport is to electrolyse water and produce hydrogen for use in FCVs. This pathway has also been modelled (Figure 3).

Where next?

The WTW methodology continues to be a valuable scientific tool for comparing the energy and GHG emissions for different fuel and vehicle options. Both within the JEC Consortium and among those in the international research community, substantial work is in progress to continuously improve the input data so that important energy and GHG-related decisions can be made more quickly and reliably on a 'well-to-wheels' basis. New developments are already in progress to validate land use change projections using remote sensing measurements and extend WTW methods to include material fabrication and end-of-use recycling. The JEC Consortium intends to remain actively involved in this exciting field for the foreseeable future.

Figure 3 GHG emissions—hybrid vehicle options (gCO_2eq/km)