Alternative fuels and energy efficiency in transport

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Abstract

In conjunction with shifts to alternative fuels it is crucial to simultaneously address the issue of energy efficiency, both at the application level (the vehicle as such) and for the entire fuel cycle. Naturally, this is especially the case for fuels based on fossil fuels but even for fuels based mostly, or even entirely, on renewables it is important - particularly for biomass with is limited resource base. In this respect, the choice between different energy carriers is heavily influenced by dilemmas linked to aspects such as: penetration degree and speed, energy resource flexibility, overall energy efficiency, well-to-wheel impacts, performance and costs. Many biofuels have the advantage of being capable of quick and easy introduction in the transport sector, but at the same time have limited total potentials. Electricity and hydrogen while not offering this quick and easy path, on the other hand is extremely flexible with regard to resource base (including to non-sustainable paths) and do not have the limitations of biofuels. Also they are, potentially, a very energy efficient option, particularly in the case of electricity. Electric vehicles have conversion efficiencies that are, generally, a factor 2-10 better than those of hydrogen, but on the other hand offer much more limited performance (notable regarding range) and possibly higher costs. Plugin hybrid electric vehicles provide an opportunity to reduce, but not necessarily eliminate these problems. The important choice in this context is not just between the main energy carriers but also within each of these (especially for the hydrogen paths). Also the (non-plugin) hybrid electric vehicle, already on the market today, promises an option of a very energy-efficient drive system within the present fuel market as well as alternative fuels. In the power supply system electric, hybrid and hydrogen vehicles may have beneficial impact on the overall system, but these benefits depend on the actual system and its operation. This paper explores these dilemmas, including studies of the link to the power supply system. A crucial focal point is the conflicts between different considerations – rapid intro vs. penetration, energy efficiency vs. flexibility of energy resource performance, costs etc.

Introduction

The introduction of new energy carriers such as biofuels, gas/biogas, electricity or hydrogen is a means for reducing fossil fuel consumption and/or GHG emissions in the transport sector. In this context, the fuel cycle efficiency with which the energy resource is converted to useful work is a crucial parameter for assessing the different resource/technology options. Naturally, this applies in particular for options based partially and entirely on fossil fuels but even for renewable energy it is frequently an issue, given that there are, in practice, few resources, even renewable, completely without problems.

At the same time other issues are involved in the decisions. Particularly flexibility with regard to energy sources, where it is particularly important for the renewable resources. Other considerations involves functional requirements and costs.

Methodology

The choice between alternative fuels such as bio-fuel, hydrogen and electricity, and between their different paths, is a complex evaluation of various aspects, also involving assumptions on the long-term development of technologies with very different development trends, as seen today. The evaluation is further complicated by the fact that the electricity/hydrogen forms part of the electricity supply system and can only fully be analysed in this context.

Various methods exist for comprehensive assessments, notably cost-benefit analysis (CBA) and lifecycle analysis (LCA). These analysis types, in principle, cover every aspect of the change to new fuels, including the impacts of buildings, technologies etc. necessary for the change (Delucchi 2003). It means that they are extremely complicated, and based on a large number of assumptions and difficult to review. A different approach, applied in this paper, is to substitute or supplement the cost-benefit analysis or lifecycle analysis with a more piecemeal approach, in which the evaluation is based on a range of partial analysis. The disadvantage of this approach is that it is more difficult to ensure a systematic approach but at the same time it increases the transparency of the assessments.

Instead of LCA/CBA approaches the paper includes findings from Well-to-Wheel impact assessments. This is a simpler method including impacts linked to the fuel cycle from energy source to the driving wheel, but not those linked to technologies, buildings etc. (Edward et al 2007).

Overview of energy carriers and drive-trains

Seen from today's viewpoint the most important energy carriers for renewable energy include: liquid bio-fuels, methane/biogas, electricity and hydrogen. All of these can be based on both fossil and renewable energy sources, including combinations.

Regardless of their respective strengths and weaknesses electricity and hydrogen have in common the strengths of having high flexibility with respect to primary energy sources and the possibility of selecting between several renewable energy sources. In contrast, liquid bio-fuels and methane, which are generally more immediately applicable options in the short term, are to a large extent confined to biomass as resource base[1].

As argued in the subsequent section this a relatively limited resource compared to its potential applications. Hence, there is a realistic risk that they are at least in part based on fossil fuels, for instance in case the demand for bio-fuels/biogas outstrips the production capacity or for cost reasons. In contrast, electricity and hydrogen offer much greater flexibility to different renewable energy sources, but also to a wide range of fossil fuels. Therefore, while by no means eliminating the problem of unsustainable sources, they are not confined to biomass on the renewable front.

At the same time electricity and hydrogen require a break with the present development of the automobile to a much greater degree, resulting in a longer time horizon, at least for its large scale application. This is due to need for both R&D, market development, a leap in the development and requirement for infrastructure.

Biomass as energy resource

There are several dimensions to the problems linked to the use of biomass as energy resource. First, biomass as a resource has an overall framework, given by the carbon flow and determined in the last analysis by the plant growth. Since, plant growth is linked to land through average yields, biomass generation implies a land demand ad a competition about land, albeit with great uncertainties. This establishes the limit for utilisation of biomass in the form of residuals (e.g. straw) and organic waste, such as the organic fraction of household waste. Hence, the utilisation of organic waste is not a means to circumvent the limit but rather to increase the efficiency of its use. At the same time, there is a large number of applications for the biomass resource besides the use as transport fuel, including for food, feed, as raw material for products, stationary energy purposes etc.

Secondly, the competition is further aggravated for the 1st Generation bio-fuel technologies, linked to specific biomass types, for instance wheat, and consequently further aggravated conflicts with other uses, such as for food. A shift to 2nd Generation technologies can reduce this link, but only within the overall framework of the biomass potential.

Thirdly, the Well-to-Wheel impacts of the biomass resource and its conversion to bio-fuel or biogas, notably with regard to fossil fuel use and GHG-emissions, have substantial influence on the overall consequences of the application of the fuels.

The European Environmental Agency, EEA, has carried out an assessment of the projected environmentally-compatible potential for energy purposes (including transport) between 2000 and 2030 in the EU-25 as well as for its 25 individual member states (European Environmental Agency, 2006). This refers to the potentials available without additional pressures on biodiversity, soil and water resources and in line with environmental policies and objectives.

Figure 1 illustrates the ratio between these potentials and the present gross energy consumption (European Commission, DG Energy and Transport, 2008) for some of these member states and for EU-15 and EU-25. It can be seen that this ratio for both the EU and Denmark, and indeed for most large member states is in the order of 10-15%.

Despite the significant uncertainty ranges around the calculated shares, the results nevertheless illustrate that ecologically sound upper limits in the EU Member Countries' biomass potential for energy purposes will imply serious restrictions on the overall contribution of biomass to transport fuels in the EU. Therefore, it is vital to utilise flexible energy carriers for any biomass utilisation in the transport sector.

Given that transport accounts for around 28% of the total gross primary energy consumption in the EU (European Commission, DG Energy and Transport, 2008), a target of 10% biomass based transport fuel by 2020 would be equivalent to around 3% of the primary energy use, everything else being equal . Hence, the biomass potentials left for other energy applications would amount to only 8%-point of the total primary energy consumption. It should be noted that the EU target has been relaxed to allow other fuels based on renewable energy to be counted towards the target. Even so, it is likely that a high fraction of the target will be met by bio-fuels in any case, partly due to inertia in the development process and partly due to the profile of the requirement. The relatively short time limit to the targets in 2010 and 2020, with no further strengthening of the requirements beyond this, probably favour alternative fuels that can easily be introduced, such bio-fuels, without punishing their limited potentials.

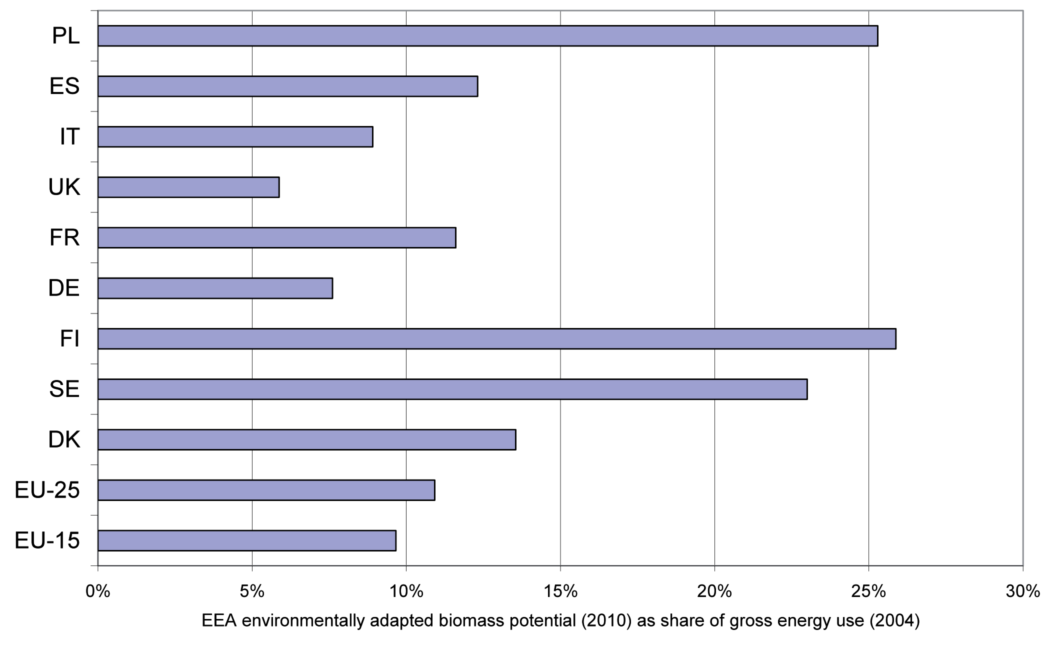

Figure 1. Ratio of EEA environmentally compatible bioenergy potentials and gross energy consumption for EU-25, EU-15 and selected member states, Poland, Spain, Italy, UK, France, Germany, Finland, Sweden and Denmark.

In conjunction with the Danish R&D-project, Renewable energy in the transport sector using biofuels as energy carriers (REBECA), two scenarios towards 2030 have been analysed (Jørgensen 2009):

- Scenario 1, reflecting roughly the Danish and EU decisions on the introduction of bio-fuels: 5,75% of transport fuel in 2010, and 10% from 2020 onwards
- Scenario 2 based on stronger penetration of bio-fuels, increasing to 25% in 2030

Both scenarios are based on the Assumption that these targets are applied with same percentages in diesel and gasoline driven vehicles in the form of ethanol based on wheat and biodiesel based on rapeseed oil.

In the project the required land has been estimated presuming that crops are grown for this purpose in the Danish agricultural area. These amount to approximately one fifth of the Danish agricultural land for Scenario 1 and 60% for Scenario 2 – in other words not feasible.

Fuel cycle of electricity and hydrogen

Electricity may be used either directly as fuel in battery-electric vehicles or plug-in hybrid-electric vehicles, or be converted into hydrogen and applied in internal combustion engine-based vehicles or in fuel cell vehicles. If electricity is used as fuel in battery-electric vehicles (BEV), this is typically supplied from the public grid, stored onboard the vehicle (typically in batteries) and used in electric motor drives. In principle, the recharging can be achieved through existing sockets, and in this case the infrastructure is very inexpensive. This is, however, a solution which imposes many restrictions on the place and speed of the recharging. Hence, in practice, more requirements and costs will be linked to this option, particularly if fast recharge is required and if the electricity consumption needs to be monitored. This is usually a very energy efficient option (Horstmann & Jørgensen 1997, Kempton et al 2001).

Hybrid-electric vehicles (HEV) are characterised by having both electric motors and internal combustion engines in its drive system (Graham 2001, Duvall 2002, Gage 2003, Lipman & Delucchi 2003, Boschert 2006). The plug-in hybrid-electric vehicle (PHEV) is a hybrid which can be recharged from the grid. It can be perceived as a BEV supplemented with an internal combustion engine-based drive. In fact, the PHEV category contains a wide range of different options, defined by factors such as:

- configuration – parallel or series hybrid, or combinations
- design principles, e.g. the distribution between electric and internal combustion engine modes
- dimensioning and operating principles

Besides the PHEV, there is a quite different hybrid-electric technology option, represented by Toyota Prius, Honda Insight and other models. This, indeed the only hybrid-vehicle type on the market at present, is a vehicle which neither must nor can be connected to the public grid for supply of energy. Instead it relies on energy from conventional fuels such as gasoline, or any fuel that can be used in Internal Combustion Engines, and the electricity storage is only used in order to improve operational conditions for the internal combustion engine.

Hydrogen can be used as a fuel in both internal combustion engines and drive systems based on fuel cells and electric motors (Padró & Putsche 1999, Ogden et al 2001, Ogden et al 2004). The latter is a much more energy-efficient solution than the former, and furthermore cleaner (the internal combustion engine will have NOx emissions even with hydrogen as a fuel). Hence, substantial variations can be found in the energy and environmental impacts of different hydrogen options, but normally even the most efficient hydrogen pathways have greater losses than the least efficient option based on electricity as fuel.

On the other hand, the vehicle range is usually considerable higher for hydrogen than for BEVs and this will in all probability continue to be the case in the future. This is linked to the costs and physical properties and the two storage mediums as described in detail below (Amos 1998, Kalhammer et al 2007).

A range of different options can be identified with regard to onboard hydrogen storage. Storage in the form of liquid hydrogen (LH_2) can achieve ranges in the same order as conventional vehicles, but this option has extremely poor energy efficiency and other weaknesses in addition. From an energy efficiency viewpoint, the most attractive solutions at present are probably compressed gas tanks (CH_2 storage) and metal hydride storages, but the latter of these still requires considerable development in order to reduce weight and costs.

Infrastructure requirements and costs constitute a major drawback in conjunction with hydrogen. In this respect, hydrogen undoubtedly involves the greatest number of obstacles of all alternative fuels. This weakness in combination with the currently shorter ranges in connection with hydrogen vehicles have resulted in the exploration of options in which liquid fuels (gasoline, diesel, methanol etc.) are converted into hydrogen onboard the vehicle. This solution involves considerable energy losses and in addition, many technical problems as well as problems of reducing the volume of the onboard conversion technology.

Hydrogen can be generated via other pathways than via electricity, notably (in a renewable energy context) by conversion of biomass through gasification or other processes (Padró & Putsche 1999, Sørensen et al 2000, Ogden et al 2004). It may also be produced from various fossil fuels, particularly natural gas or coal. From a sustainability point of view, however, there is little point in shifting to hydrogen if this is based on fossil fuels, even in the long term. Hydrogen produced by electrolysis based on electricity from the present Danish or European electric grid and used as vehicle fuel generally has much higher energy consumption and CO_2 emissions than the present fuels used for the same applications.

The non grid-connected HEV is generally not used in order to shift fuel but only to improve the energy efficiency of the vehicle. In principle, it can use any liquid or gaseous fuel, including hydrogen, bio-fuels, biogas and others. Seen from today's point of view, this is not a very likely option. However, this may change in the longer term if and when the hybrid drive train type is developed into a state-of-the-art technology, particularly if the fuel cell technology is not successful in the long term or only achieves a limited application. This hybrid type is frequently seen as a competitor to the fuel cell and as a very efficient drive system in the long term (Edwards et al 2007). While it will probably not reach the same energy efficiency levels as fuel cell drive systems, it will not need a break with the present automobile technologies, fuels and infrastructure. It is likely to remain a lower-cost option compared to fuel cells unless the latter experiences a large-scale breakthrough.

Energy efficiency of fuel-cycle of electricity and hydrogen

Limiting the scope to electricity and hydrogen the case can be perceived, ultimately, as a question of different ways to use electricity as fuel in vehicles, though hydrogen may be generated without being based on electricity.

The choice between electricity and hydrogen is heavily influenced by dilemmas and trade-offs, including (Jørgensen 2008): direct and indirect energy and environmental impacts (including impacts through energy and transport systems); vehicle range between refuelling; weight and volume of onboard energy storage, fuel cells and the drive system in general; costs of purchase and operation of vehicle and fuels; durability of key components, particularly those with high costs (notably battery and fuel cell); demands to infrastructure for fuels and technical backup; need for a break with the present development of technologies and fuels; flexibility, not least with respect to energy resources.

For electricity used in electric vehicles, the main losses involved are conversion losses in the electric motor, losses in the battery and recharging losses. The following assumptions have been used (Horstmann & Jørgensen 1997, Kalhammer et al 2000, Gaines & Cuenca 2000, Delucchi & Lipman 2001, Kempton et al 2001, Delucchi 2003, Lipman & Delucchi 2003, Duvall 2004, Horstmann 2005, Kalhammer et al 2007):

- conversion efficiency electric motors: 80-85% for present motors and 90-92% or even higher in future advanced electric vehicles
- efficiency of batteries: 70-85% (depending on the battery type and not only on the development stage and hence not necessarily developing)
- recharging efficiency: efficiencies in the order of 95%
- regeneration of braking losses, assuming about 70-75% of braking losses to be recovered and resulting in improvements of the total average vehicle energy efficiency by 15-20%

In addition to the gains in conjunction with the electric motor as such, electric drive systems, including the ones based on fuel cells, can be made simpler and more efficient by leaving out the transmission entirely and thereby reducing losses and weight. Moreover, idling losses are eliminated and also they are better suited for part load. The development in control and power electronics has enabled the application of lighter AC motors.

The energy efficiency of hydrogen used in vehicles based on either fuel cell or ICE drive trains is the product of the following main factors (Padro & Putsche 1999, Kempton et al 2001, Ogden et al 2001, Sørensen et al 2001, Delucchi 2003, Koljonen et al 2004, Ogden et al 2004, Edwards et al 2007, Kalhammer et al 2007):

- in FC vehicles – average conversion efficiency of fuel cells and electric motors: between 37% and 55%
- in internal combustion engine vehicles – average conversion efficiency of the ICE, including idling losses and transmission losses: 15-18%

- efficiency of onboard energy storage, including boil-off losses etc.: 93-100% (depends heavily on storage type and driving patterns)
- refuelling efficiency: 95-100%
- hydrogen generation by electrolysis: 75% in present alkaline technologies and up to 92% in future advanced polymer electrolysis
- liquefaction of hydrogen for the alternatives based on liquid hydrogen: 70-72%
- in FC vehicles – regeneration of braking losses, improving the vehicle efficiency by between 0% (at present) and 15% (in the longer term)

Figure 2 shows the calculated specific electricity consumption per km off grid for an average Danish passenger car being a battery-electric vehicle (BEV) and a variety of hydrogen-based options (internal combustion engine/fuel cell, LH_2,/CH_2), respectively, both present state-of-the-art and advanced technologies. Hydrogen is assumed to be generated by electrolysis. It can be seen that all hydrogen options have a higher specific electricity consumption than both of the battery-electric vehicle options. At the very best, the hydrogen solutions (fuel cell and CH_2) are about a third poorer in terms of energy efficiency than the present battery-electric vehicle; and at worst, up to about a factor 10 poorer (ICE/LH_2).

Figure 3 shows the calculated CO_2 emissions for the electricity consumption figures in Figure 2, assuming that it is covered by average electricity in the Danish electricity supply system as of 2004 (Danish Energy Authority 2007a). The estimated CO_2 emissions are also shown assuming that hydrogen is generated through steam-reforming of natural gas (Ogden et al 2001). Finally, the calculated average CO_2 emissions (including upstream emissions) of Danish passenger cars – new registrations – are shown (Road Safety and Transport Agency 2007, Edwards et al 2007). The graphs illustrate the point that the rationale of hydrogen is to serve as energy-carrier for renewable energy. But based on natural gas reforming, the best hydrogen options can give substantial CO_2 reductions compared to the present conventional vehicle (up to a factor 2-3). And battery-electric vehicles will have considerable lower CO_2 emissions even based on the present electricity system. This provides a conservative assessment of both electric and hydrogen vehicles, partly because the electricity supply system is planned to be improved considerably over the coming years (Danish Energy Authority 2007b) and partly because it ignores the benefits achieved by using electric and hydrogen vehicles as flexible electricity demand (Nielsen & Jørgensen 1997, Sørensen et al 2000, Lund & Münster 2006a, Lund & Münster 2006b). A further perspective could be the utilisation of electric or hydrogen vehicles not only passively as flexible loads on the demand side but also actively as decentralised power generation units, e.g. (Kempton et al 2001, Gage 2003, Kempton & Tomié 2005a, Kempton & Tomié 2005b).

Vehicle range

The range of the vehicle can be a serious issue in conjunction with alternative fuel vehicles. It is determined as the combination of onboard energy storage and the specific electricity consumption of the vehicle. This means that it may be increased not only by increasing the energy storage but also through improved specific energy consumption.

The different hydrogen storage options have energy densities in relation to both volume and weight that are 5-10 times higher, or more, than equivalent batteries. Even though the conversion of electricity has a higher efficiency than hydrogen, this in no way compensates for the difference in energy densities.

Figure 4 illustrates the problem by showing calculated weights of the battery and hydrogen storage (compressed hydrogen) for a passenger car. Four different battery technologies are included based on the following projection assumptions for high volume production runs (100,000 units or more) and for typical battery sizes for a passenger car – from studies carried out by (Delucchi & Lipman 2001):

- lead/acid (Pb/acid) – energy density (as electricity) 30-35 Wh/kg, specific cost 10-12 Euro/kg (equivalent to 0,3-0,4 Euro/Wh), lifetime 770 cycles
- nickel/metal hydride of second generation (NiMH 2G) – energy density 60-75 Wh/kg, specific cost 30-45 Euro/kg (equivalent to 0,46-0,75 Euro/Wh), lifetime 670 cycles
- nickel/metal hydride of fourth generations (NiMH 4G) – energy density 85-110 Wh/kg, specific cost 28-48 Euro/kg (equivalent to 0,27-0,55 Euro/Wh), lifetime 1330 cycles
- lithium/ion (Li/ion) – energy density 120-150 Wh/kg, specific cost 35-65 Euro/kg (equivalent to 0,25-0,70 Euro/Wh), lifetime 1100 cycles

The NiMH 2nd generation battery is the current state-of-the-art for traction purposes with some development towards NiMH 4th generation. The latter can be perceived as an improved battery at roughly the same costs per kg. The Pb/a battery is the former state-of-the-art for traction, illustrating the development over the recent couples of decades.

In addition to the batteries, two hydrogen onboard storage options are included in the graph (Ogden et al 2001, Edwards et al 2007):

- 300 bar aluminium tank (present state-of-the-art) – energy density (as hydrogen) 1100 Wh/kg, specific cost around 13 Euro/kg (12 Euro/kWh)
- 600 bar composite. – energy density (as hydrogen) 2200 Wh/kg, specific cost 21 Euro/kg (12 Euro/kWh)

The results are hypothetical calculations and not practical experiences and also that it does not show the full picture since the weight of the fuel cell will offset some of the difference. In practice, it would not be possible to provide vehicles with batteries or hydrogen storages which are equivalent to this, e.g. correspond to half of the vehicle weight. Nevertheless, the graph illustrates the difference between batteries and hydrogen. With the NiMH battery technology shown, it is not possible in practice to extend the range beyond approximately 150 km based on 2nd generatio*n* technology and 200-250 km based on

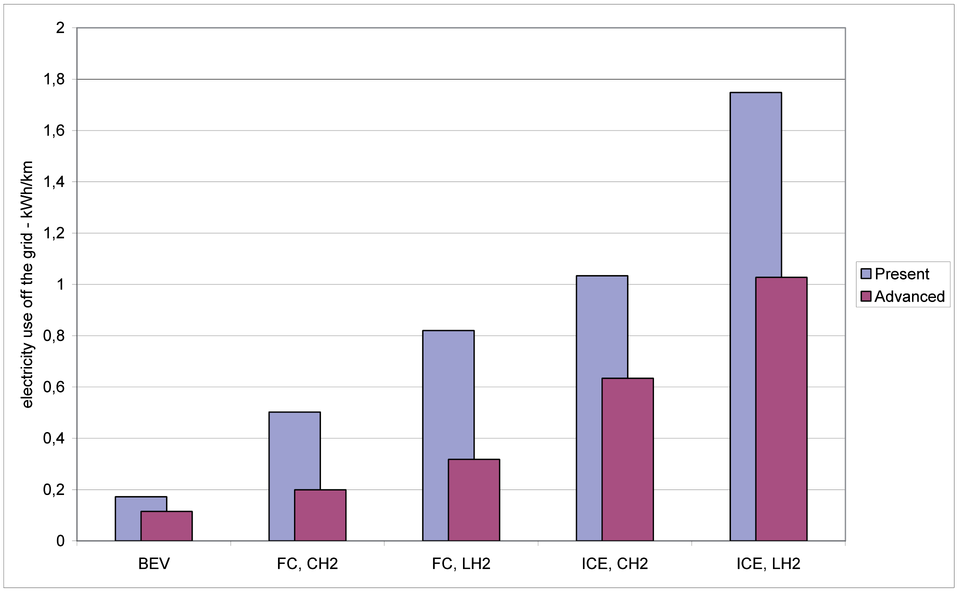

Figure 2. Estimated specific electricity consumption per km off the grid for different electric and hydrogen automobiles, specified in the text. FC = Fuel Cell; ICE = Internal Combustion Engine; CH2 = compressed hydrogen; LH2 = liquid hydrogen. Source: the author.

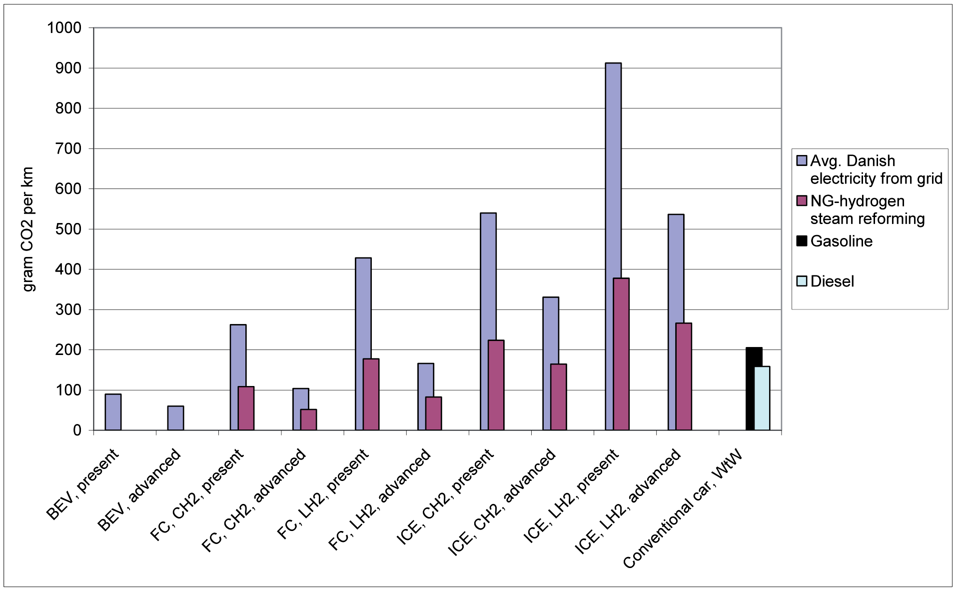

Figure 3. Average CO_2 emissions per km for the electric and hydrogen automobiles of Figure 2 for either average electricity from the Danish grid or hydrogen generated by means of natural gas reforming. Also the estimated Well-to-Wheel CO_2 emissions of the same vehicle driven by conventional gasoline or diesel drive systems. Source: Edward et al 2001; Road Safety and Transport Agency 2007; Danish Energy Authority 2008; and the author.

4th generation batteries. Even with the advanced Li/ion battery, it will not in this calculation be realistic to extend the range much beyond 300-350 km. For hydrogen, on the other hand, it will be feasible, though not unproblematic, to achieve ranges in the order of 600 km even with the present technology; and with advanced types (higher compression and lighter material), it may be possible to achieve this with only minor problems.

Discussion

Bio-fuels are in all likelihood confined to a limited role in the transport sector, unless combined with a substantial improvement of the fuel-economy of the vehicle (e.g. through introduction of hybrid vehicles) or similar reductions of the transport energy consumption.

Electricity and hydrogen on the other hand have much greater flexibility than liquid bio-fuels and biogas. They at the same time can offer extremely energy efficient solutions but at the same time there is a great variation in the efficiency be-

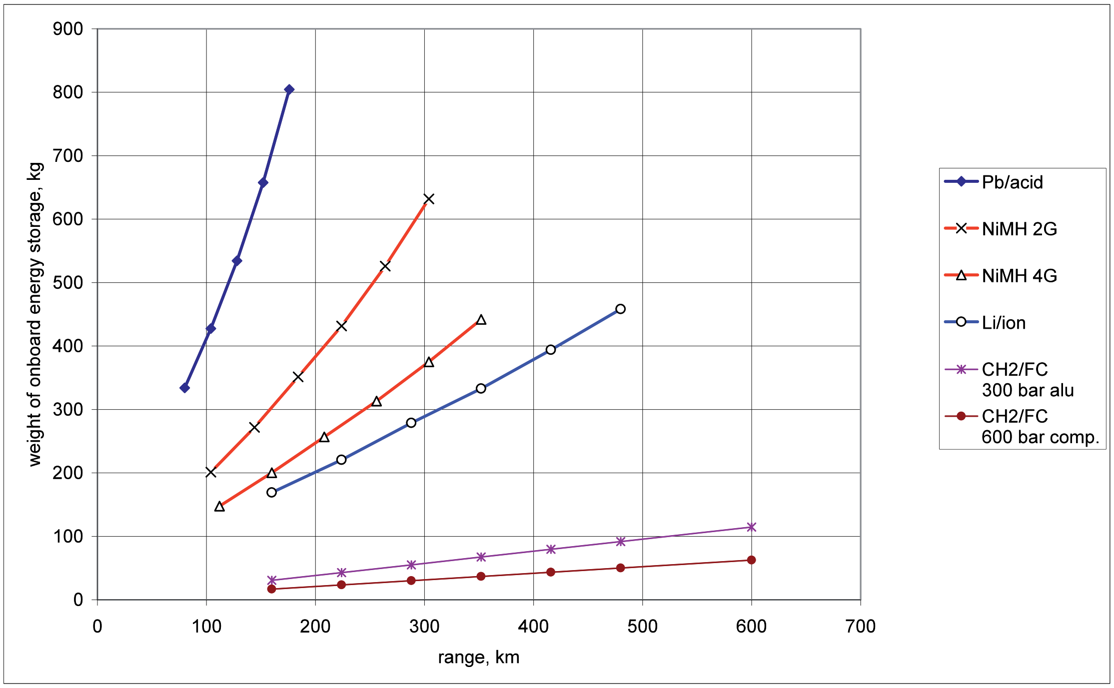

Figure 4. Calculated weight vs. range with selected battery types and hydrogen onboard storage (compressed gas) of an average automobile in Denmark.

tween different solutions and different designs of each solution - around an order of magnitude or more. Particularly hydrogen shows a great variation.

Figure 5 shows the characteristics of different electricity and hydrogen technologies with respect to specific electricity consumption (kWh electricity per km) and range (km). Electrical propulsion based on today's technological level ("Present EV") results in a very efficient fuel cycle but also a limited range. Advanced electrical technology ("Advanced EV") may lead to a considerably greater range and, at the same time, probably an even better fuel cycle efficiency, potentially creating vehicles that can be used for most purposes. On the other hand, there may still be a need for vehicles with longer ranges – hence, providing a potential role for hydrogen.

Hydrogen internal combustion engine vehicles could increase ranges considerably, but at the expense of the fuel cycle efficiency. In particular, liquid hydrogen applied in internal combustion engines ("LH$_2$, ICE") has very poor energy efficiency characteristics but also a scope for very long ranges, whereas onboard storage in metal hydrides or as compressed gas ("CH$_2$/MeH, ICE") gives better fuel cycle efficiency and shorter range. Fuel cell technology combined with liquid hydrogen storage ("LH$_2$, FC") or storage by means of metal hydride or compressed gas tank ("CH$_2$/MeH, FC") would at the same time increase the range and improve the fuel cycle efficiency.

Range is more important than energy efficiency in the development of markets for motor vehicles, in particular for passenger cars, unless instruments (e.g. energy taxation) are applied to influence the markets. In strategies to promote Zero Emission Vehicles in general without attempts to favour BEVs/PHEVS the hydrogen/fuel cell options will tend to win, such as has happened in conjunction with the Californian ZEV-mandate. Since the former generally is the more efficient option, it would be beneficial to use instruments to increase their share, e.g. by means of taxation policies.

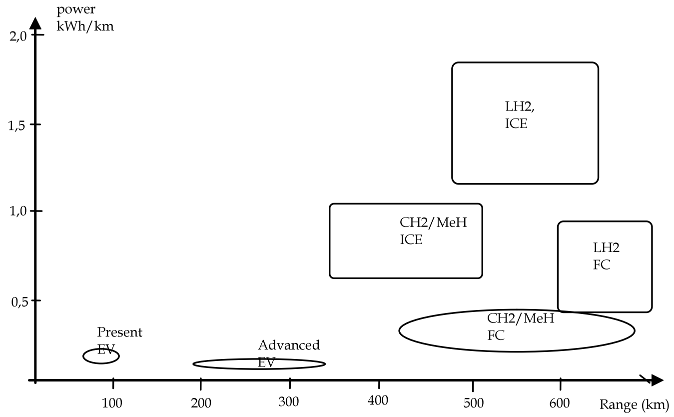

Figure 5. Specific electricity consumption vs. range of different electric and hydrogen vehicles

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Endnotes

1 At least with acceptable fuel cycle conversion efficiencies.