Renewable energy and efficiency improvements in the transport sector

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1 - SYNOPSIS

Fuel cycle efficiency can serve as a tool for reducing energy use and CO2-emissions of transport. But it cannot replace the need for comprehensive transport planning strategies.

2 - ABSTRACT

Based on a Danish study, the potentials and limitations for energy conservation and reduction of CO2-emissions by means of fuel cycle efficiency improvements and introduction of renewable fuels in the transport sector are studied. Different energy cycles (based on e.g. electric propulsion, hydrogen, biofuels) are compared. Also, the scope for resolving transport sector problems by means of renewable fuels and energy cycle efficiency improvements is assessed, especially with a view to the time perspective. Fuels based on both fossil and renewable energy are evaluated. The main aspects covered are fuel use, energy cycle emissions (particularly CO2) and land requirements. For renewable fuels, the land requirement - which can be considerable - is a particularly important factor, especially in densely populated countries.

It is concluded that, among the energy carriers for renewable fuels, electric and hydrogen propulsion (including fuel cells) have much higher energy cycle efficiencies than biofuels and other biomass derived fuels, thus requiring less resource inputs to met given fuel demands (especially land use). Comparing electric and hydrogen, it is not possible to choose one single "best candidate" since they perform supplementary roles in a strategy for sustainable transport. Electric vehicles generally represent the most efficient energy cycle but they are limited to short driving ranges, at least when based the present battery technology. If longer ranges are required, hybrid and hydrogen propulsion can be options. Technological development (batteries, hydrogen storage and fuel cells) can influence these priorities. Moreover, technological measures should be regarded as a supplement to, and not substitute for, other transport planning measures. In particular, the issue of the transport demand is important, especially in the short term where most of the technological improvement measures are found to have limited effect.

3 - INTRODUCTION

Given the CO2-reduction targets in the transport sector on the one side and the continuing growth in transport demand and traffic on the other, there is a considerable demand for improved fuel economy of vehicles and/or switch to fuels with low CO2-emissions. On this background, cleaner vehicles are required to meet the targets if the growth of transport demand in general and car driving in particular is allowed to continue. On the other hand, if these vehicles are not provided (or delayed), this would reinforce the need to curb transport demand.

While there has been substantial progress with regard to most other emissions (with further improvements being anticipated), fuel economy, and consequently the specific CO2-emissions, of passenger cars in Denmark has shown little improvement over the last 15-20 years - despite substantial potentials for higher fuel efficiency

(Jorgensen 1998a; Jorgensen 1998b). In coming years, fuel economy standards of passenger cars may even start to deteriorate as a consequence of the increasing requirements to performance, safety standards, comfort etc. This reflects a general trend: the vehicle efficiency improvements that have taken place are offset by increasing demands. In particular, the demand for more powerful vehicles is a key problem, leading to engines being operated at still lower loads and hence at reduced efficiency. Also, the growth in air-conditioning in new vehicles - even in a cool climate such as the Danish - is likely to deteriorate the fuel economy.

Instead, fuels based on renewable energy may offer an option for reducing both CO2-emissions and the dependence on fossil fuels. On the basis of the conflict between the environmental targets and the actual development, renewable fuels could be seen as a simple necessity the make the ends meet. In fact, such “renewable fuels” are frequently considered as a virtually pollution-free, and even problem-free, option that would liberate us from any limits and restrains in transport as well as in any other activity in society, see e.g. (Scheer 1993).

In contrast, approaches relying entirely on the provision of clean fuels are strongly criticised by Amory Lovins of the Rocky Mountain Institute (RMI) of Arizona, USA. Since the 1970’s, Lovins has been a strong proponent of energy efficiency improvements at end use level (Lovins 1973) and similarly has been an international pioneer with respect to assessing improvement potentials. In recent years, he has participated in the development of the “Factor 4” concept - i.e. the notion that it is possible to halve the use of resources while doubling the living standard - in conjunction with E. U. von Weizsäcker among others (Weizsäcker et al 1997). In the 1990’s, a major theme for Lovins has been the development of a “hypercar” with a fuel economy 5-10 times better than the present average of passenger cars, while maintaining or even surpassing the present automobile with regard to size, performance, safety, comfort, costs etc. (Lovins et al 1993; Lovins 1998). According to Lovins, this can achieved through integrated design based on “leapfrog technologies” rather than refinement on present designs, and he envisages that such a vehicle is not only possible but in the process of emerging. Indeed, Lovins is so sure of this that he opposes the use of fuel price increases to curb transport demand (Lovins & Lovins 1995). Hence, the focus on end use efficiency in this approach has two-sided edge: one the one hand against “clean fuel” strategies and on the other hand against strategies emphasising the need for a comprehensive transport strategy covering transport demand and traffic system aspects in addition to the improvement of the fuel cycle efficiency.

This paper evaluates different aspects of this discussion. First, in the following section, the Danish transport policy context is outlined. Section 5 concerns different aspects of the fuel cycle efficiency concept. The remaining part of the paper analysis different options for improving the fuel cycle efficiency. In Section 6 the scope is limited to fuel shifts (i.e. to the provision of different fuels for the existing vehicles) while Section 7 covers the potentials for fuel cycle efficiency improvements in broader terms, including vehicle improvements (beyond drive train measures).

4 - TRANSPORT SECTOR TARGETS AND POLICIES IN DENMARK

“Energy 2000” for the first time placed the issue of CO2-reductions on the agenda of official energy planning in Denmark, establishing a reduction target of 20% by the year 2005 (compared to 1988) and aiming at a 50% reduction by the year 2030. For the transport sector, however, a separate plan was adopted with less stringent reduction targets: a stabilisation of the emissions by the year 2010 and a 25% reduction by the year 2030 (Ministry of Transport 1990). This modification of the reduction targets, which has been confirmed in subsequent governmental transport action plans (Ministry of Transport 1993; Ministry of Environment and Energy 1996; Ministry of Transport 1996), has been explained by greater problems meeting the different targets of the transport sector than in the energy sector as such - though this claim has never been substantiated.

Indeed, a different perspective, based on ecological space considerations, would point to much greater reduction requirements in a rich country such as Denmark than those established by the Danish energy planning. Assuming, in accordance with IPCC assessments (IPCC 1996), that the global CO2-emissions should be (at least) halved by the year 2030, that the world population double, and that the rest of the world reach the same transport standard as Denmark, the required reduction of the Danish CO2-emissions would be in the order of 90-95%.

In practice, there are many indications that even the modest reduction targets laid down by the Ministry of Transport will not be met. The projected growth of the official Danish transport demand prognosis will, all other factors being equal (i.e. with frozen transport sector efficiency), lead to an increase in the CO2-emissions by 20-25% by the year 2005 and by about 50% in 2030 (Ministry of Environment and Energy 1996). Indeed, there are ongoing considerations whether the CO2-reduction targets of the transport sector should be modified, that is to adapt the targets to the actual achievements (Ministry of Finance 1998).

This provides the backdrop for considering the role of renewable energy fuels in the transport sector in Denmark. On the background of the growing conflict between the targets and the actual development, the renewable fuels could offer an option for avoiding addressing unpopular decisions concerning restrictions on traffic - or even decisions to enforce fuel economy standards.

5 - THE CONCEPT OF FUEL CYCLE EFFICIENCY

This section covers different aspects of the fuel cycle efficiency concept. First the concept is defined and treated in generic terms (5.1), next there is an overview of different fuel cycles of renewable fuels (5.2) and finally the special problems in conjunction with grid-connected electricity generating renewable energy sources (5.3).

5.1. Definitions

The fuel cycle efficiency describes the total efficiency of the conversion cycle from primary energy source to the mechanical energy driving the vehicle (Johansson 1992; Jorgensen 1998). The term is used regardless of whether the primary energy source is fossil or renewable. Most renewable fuels in a Danish context would be based on energy from the sun either directly or indirectly. Examples of direct paths are photovoltaics (converting solar energy to power) and biomass (converting solar energy to biomass), whereas wind power is an example of utilisation of the indirect effects of solar energy. Therefore, it is appropriate to define the fuel cycle efficiency of renewable fuels using the solar radiation on a horizontal area as reference. However, the primary application of the concept in this context is for calculation of the land requirements for different renewable fuels and therefore the fuel cycle efficiency in this paper is defined in terms of land area needed to cover a certain energy demand.

The fuel cycle can be divided into two main sub systems: the energy system and the vehicle system (Jorgensen 1998). The *energy system*, covering the stationary part of the fuel cycle, is responsible for production and distribution of fuels to the vehicle, including extraction/cultivation/harvesting, conversion/refining and distribution. The *vehicle system* covers the moving part of the fuel cycle - the vehicle - and describes the conversion of fuel to mechanical energy. The losses of the vehicle system are determined partly by the vehicle load (air drag, rolling resistance, braking losses, onboard accessories) and partly by the efficiency of the drive train and energy storage.

It should be noted that the paper is confined to the fuel cycle. Hence, it does not deal with life cycle analyses (LCA) - that is, analyses taking into consideration the energy and environmental impacts of the production and discarding of the technologies used. A LCA perspective could impact the findings considerably, especially for fuel cycles based on new technologies (frequently of considerable weight) but at the same time it would require a substantial research effort which is beyond the scope of the research on which the paper is based.

5.2. Fuel Cycles of Alternative Fuels

In keeping with the definition of the fuel cycle efficiency, it is determined by energy system and vehicle system factors.

On the *energy system* side, the renewable energy sources that are pertinent in this context are based on conversion of solar energy to either electricity or biomass. The electricity can either be used directly in electric vehicles or converted to hydrogen. Biomass can be converted to either biofuels or hydrogen, or it may be used as fuel input for power generation. A key factor governing the efficiency of bioenergy fuel cycle is the conversion of solar energy to biomass (the photosynthesis), generally operating at very low conversion efficiency (in the order of 0.5%).

As far as the *vehicle system* is concerned, there are three principal types of propulsion systems which can be used as energy carriers for renewable transportation fuels: electric propulsion, hydrogen propulsion and biofuels. Hydrogen and biofuels can be used in drive trains based on either conventional internal combustion engines, on fuel cells, or on hybrid configurations. In this paper, the hybrid configurations have been excluded from the comparisons to keep the presentation within the limits of a short paper.

5.3. Renewable energy in the power supply system

In Denmark, renewable electricity generation systems are usually connected to the public grid and probably will continue to be so in the future. In particular, this link serves an important purpose as "storage" for fluctuating renewable power sources such as wind power and photovoltaics.

Grid-connected renewable energy sources, usually cannot be seen as linked directly to the power demand of the vehicles and therefore it is not possible to assign a specific part of the primary energy input to the electricity consumed. Instead, the consequences for the primary energy input is determined by means of a systems consideration based on not only the actual fuel mix but also the calculation principles applied (Jorgensen 1998a).

The standard convention (in Denmark) is to apply a marginal consideration to determine the fuel input of a given kWh of power - i.e. to assign the fuel input on the basis of the presumed marginal power generation technology to be applied to cover the extra power demand - and, in Denmark, the marginal power generation technology is generally assumed to be a coal-fired power plant without heating utilisation. This generally provides very unfavourable conditions for the assessments of technologies on the demand side (e.g. electric vehicles) - since it means that they can take advantage of neither clean fuels nor the cogeneration benefit. Hence, there is a risk that these marginal assessments rule out options that would be considered advantageous in a total systems analysis. Therefore, a decision process based entirely on marginal comparisons does not necessarily lead to the best overall solution.

If renewable power generation capacity is established in parallel with the application of electric or hydrogen, this could be seen to be the marginal power supply option. In this case, the fuels could, in principle, be seen as entirely based on renewable energy.

An analysis based on average operating conditions (that is, the average over the fuel mix of the actual time) would provide a different picture. At the same time, however, such analyses have certain problems from a systems perspective, including the fact that the utilisation of an “average kWh of power”, in effect, changes the conditions for the rest of system (though in most cases the damages are limited as the power load in question is a small fraction of the total power demand). Also, in a power supply system with extensive utilisation of combined heat and power generation (as in Denmark), principles have to be established as to the split of the cogeneration advantage between the power and heating side - even in an analysis based on average conditions. Here, the conventional approach has been to assign all of the advantage to the heating side and therefore assume that the power is generated without heating utilisation.

There are no simple solution to this problem and consequently no single answer as to the preferable approach. The fundamental response is to carry out total systems analyses of the power system with and without the electric and hydrogen vehicles (as is being done in an ongoing project between Technical University of Denmark and Riso National Laboratory in continuation of the research on which this paper is based). To supplement this quite elaborate working process, the range of the results can be illustrated by applying different viewpoints. In this paper, two main perspectives are used: average operating conditions (with and without heating utilisation) and a marginal consideration, assuming that sufficient renewable generating capacity is established to cover the demand.

6 - SWITCH TO RENEWABLE FUELS

This section focuses on the potentials in conjunction with shift to different fuels, notably fuels based on renewable energy. As described above (see Section 5.3), there can be different approaches to the analysis of primary energy effects of grid-connected renewable energy plants. Therefore, Section 6.1 assesses the effects on fuel input and CO2-emissions of electric and hydrogen vehicles based on electricity from the public grid. Section 6.2 evaluates the land requirements for different renewable fuels and finally Section 6.3 compares the different roles of electric and hydrogen vehicles.

6.1. Primary Energy and CO2 Emissions of Grid-connected Renewable Energy

In the following, the impact on CO2-emissions is investigated for electric vehicles and different hydrogen technologies, based on the average fuel input of the present Danish power supply - almost entirely on coal-fired (National Energy Agency 1998). Since coal's specific CO2-emission (gram/MJ fuel) is high, CO2 is inevitably a critical factor in any vehicle based on electricity from the present Danish power system.

A high percentage - about 80% - of Denmark's power is produced as cogeneration (National Energy Agency 1998). The actual electricity consumption, however, is not necessarily met by cogeneration, since this depends (among other factors) on the heating and power demand at the time and also on the calculation principles (marginal/average considerations) applied (Jorgensen 1998a). Moreover, there are different principles concerning the split of the cogeneration advantage (i.e. the fuel saving resulting from the combined production) between the electricity and heating sides of the system. To illustrate the range of the results, the CO2-emissions is studied for the two situations: with and without cogeneration.

Figures 1 and 2 show the calculated CO2-emissions for an average passenger car with electrical propulsion as well as with different hydrogen technologies and biofuels (Jorgensen & Nielsen 1998). Figure 1 is based on today's technological level and power supply system, whereas Figure 2 shows a projection of technologies and power system to the year 2030.

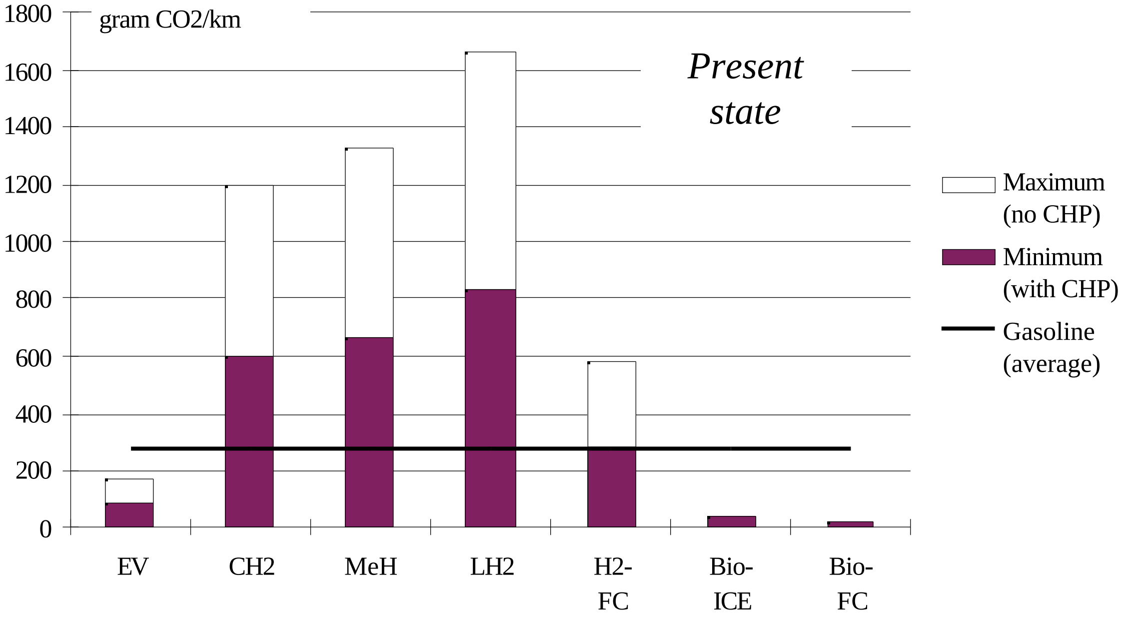

Figure 1. *Simulated specific CO2-emissions for passenger car with different drive systems: battery electric (EV); hydrogen ICE with compressed gas (CH2), liquid hydrogen (LH2) and metal hydride (MeH) storage; hydrogen fuel cell (H2-FC); biofuel ICE (Bio-ICE); and biofuel fuel cell (Bio-FC). Compared to equivalent gasoline ICE vehicle. Present state technology and power system (in Denmark).*

The CO2-emissions for these vehicles have been computer simulated for urban driving patterns and compared to a equivalent gasoline driven vehicle. For this, simulation models developed in conjunction with the project have been used (Jorgensen 1998a; Jorgensen & Nielsen 1998). The projected power system of the year 2030 is based on the official Danish energy plan (Ministry of Environment and Energy 1996). Here coal is replaced by natural gas and also the share of renewable energy is expected to rise to 50%.

The hydrogen technologies include three different hydrogen technologies based on internal combustion engine (ICE) drive trains - liquid hydrogen, compressed gas storage and metal hydride storage - and one based on fuel cells (FC). The choice of on-board storage technology is particularly important for ICE drive systems since they utilise the energy less efficiently than FC systems. Biofuel vehicles include both ICE and FC drive systems. The hydrogen is assumed to be generated by electrolysis, using the above assumptions regarding efficiency.

As shown by Figure 1, electric vehicles can lead to a substantial reduction of the CO2-emissions, even based on the present power generation and even for the worst case situation, that is power generation without cogeneration. This applies for urban driving patterns, whereas the gains are much more limited in case of highway driving patterns. Indeed, in the latter driving patterns, CO2-emissions with the present power supply system are roughly the same for electric and gasoline vehicles (without cogeneration). Also, if a diesel rather than a gasoline driven vehicle is used as reference, the emission benefits of the electric vehicle would more or less disappear.

Based on the present power generation, all of the hydrogen technologies, even the FC drive train, would result in significantly higher CO2-emissions than their gasoline counterpart even in the best case situation with cogeneration. Only the FC version can match the gasoline vehicle, and only in case of cogeneration.

Based on the projected power supply system for the year 2030 (Figure 2), all of the hydrogen ICE technologies match the CO2-emissions of the gasoline vehicles of the year 2030, provided the power is based on cogeneration. Without heating utilisation, the 2030 hydrogen ICE vehicles perform poorer than the gasoline vehicles of 2030, while they offer an improvement over the present gasoline vehicle in terms of CO2, even without cogeneration. The fuel cell vehicle reduces CO2-emissions even compared to the gasoline vehicle of the year 2030 and even without cogeneration in the power system.

It should be noted that, in a scenario of fossil fuel hydrogen, electrolysis based on power from the public grid would hardly be the first choice since natural gas reforming would probably be both cheaper and less CO2-polluting (Cannon 1995; Ogden 1997). Hydrogen generation by electrolysis probably is the most viable path for renewable hydrogen, but in a transition period natural gas reforming could be a step towards this goal.

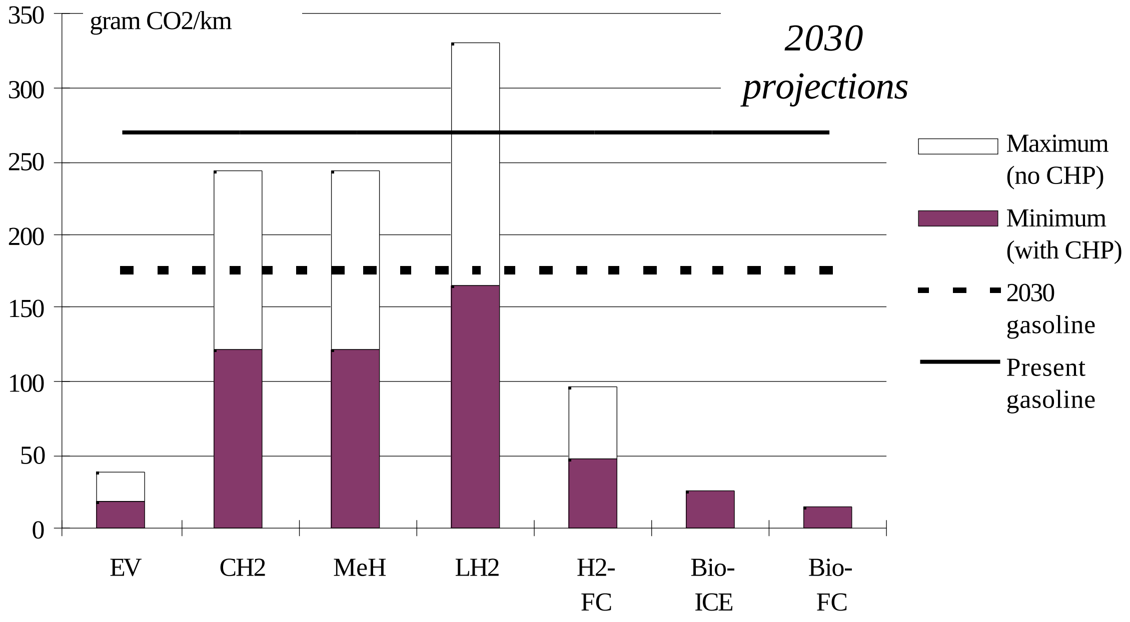

Figure 2. *Simulated specific CO2-emissions for same vehicles as in Figure 1, except projected technology level and power system of the year 2030. Compared to both present gasoline vehicle and projected gasoline ICE passenger car of the year 2030.*

6.2. Land Requirements of Renewable Fuels

At a global scale the influx of energy from the sun is several thousand times greater than the present total energy consumption for human purposes, and even in the energy intensive OECD countries the solar energy influx is roughly 800 times higher than the present demand (Scheer 1993). Hence, even with poor utilisation and substantial growth in total energy demand, the physical energy resources will still be well above the demand.

In practice, however, the resources are constrained, since the limiting factor is not the total resources, but the construction and operation of the technologies needed to convert the solar energy into useful energy: wind or solar power plants, cultivated fields, dams for hydropower plants etc. In particular, the land requirements to convert the solar energy can be a considerable, especially in densely populated countries. To a certain extent, the utilisation of land for renewable energy can be combined with other forms of utilisation - e.g. solar heating panels integrated with roof constructions or forests being used at the same time for biomass growing and recreation purposes - but generally this reduces the problem rather than solving it. Therefore, there are good reasons for utilising renewable energy sources as efficiently as possible. The significance of the fuel cycle efficiency is that it determines the efficiency in the utilisation of land, and hence translates the energy demand into the land needed to cover the demand. Table 1 illustrates the land requirements for generation of renewable transportation fuels. It shows the estimated required land for the annual generation of fuels for a medium-sized passenger car (corresponding to the average of the Danish passenger car stock) as well as the percentage of the total Danish land area (43,000 squarekilometres) required to cover the domestic transport energy demand in 1996 (158 PJ).

Table 1. Land needed to cover the annual demand of an average passenger car and % of Danish land to cover total transport energy demand in Denmark (Jorgensen 1998; Jorgensen & Nielsen 1998).

	LAND FOR AVG. PASS. CAR	LAND, TRANSPORT ENERGY
	m2	*% of total Danish area*
EVs, photovoltaics	15-30	0.1-0.3
EVs, wind power	80-200	0.8-2.1
EVs, biomass power (no CHP)	1000-1900	10-18
EVs, biomass power (with CHP)	500-1000	5-10
Hydrogen, ICE, photovoltaics	60-250	0.6-2.3
Hydrogen, FC, photovoltaics	30-100	0.3-0.9
Hydrogen, ICE, wind power	350-1500	3.3-15
Hydrogen, FC, wind power	190-750	1.9-7.0
Hydrogen, ICE, biomass	2200-7600	21-72
Hydrogen, FC, biomass	1100-3100	10-30
Biofuels, ICE	1900-3800	18-37
Biofuels, FC	1000-1900	9-18

The table is based on the following assumptions concerning the energy losses in each stage, generally related to Danish conditions (Jorgensen 1998; Jorgensen & Nielsen 1998):

- conversion of solar energy to power: 10-15% (photovoltaics); 2-5% (wind parks, land based); 3-7% (wind parks, sea based); 8-25% (individual windmills); conversion of solar energy to biomass (photosynthesis): 0,4-0,6% (150-200 GJ/hectare); conversion of biomass to biofuels: 60-70% (presuming by-products are utilised); conversion of biomass to hydrogen: 60-75%; conversion of electricity to hydrogen (electrolysis): 80-95%
- distribution losses for electricity: 8%
- distribution and handling losses for hydrogen, including compression energy, excluding liquefaction energy for liquid hydrogen: 8-15% (gaseous hydrogen); 15-25% (liquid hydrogen); liquefaction losses (hydrogen): 30-40%
- ICE drive train efficiency, including transmission: 15-22%; electric motor efficiency, incl. transmission: 70-80% (present); 85-91% (advanced motor);
- battery efficiency (incl. charging, excl. weight penalty): 70-80% (present); 75-85% (advanced); efficiency of onboard hydrogen storage (excl. weight penalty): 85-95% (gaseous hydrogen); 75-90% (liquid hydrogen)
- weight penalty (per cent to be added to specific electricity consumption): 25-30% (present electric vehicles); 10-15% (advanced electric vehicles); 15-25% (hydrogen ICE vehicles with compressed gas tanks); 5% (liquid hydrogen vehicles); 15-35% (hydrogen fuel cell vehicles);
- onboard fuel cell efficiency (electricity): 40-50%
- regeneration of braking energy: 20% for electric vehicles (including fuel cells)

The intervals cover two aspects: the spectrum between the most energy-efficient and the least energy-efficient technologies today; and the development potential in coming years.

As can be seen from Table 1, the fuels based on biomass are clearly distinguished from the remainder. Whereas the former typically need around 25%-30%, or even more, of the total Danish land area to cover the annual transport energy demand (around 20% of the total primary energy demand in Denmark), the land requirements for the latter typically are up to a factor 50-100 lower. The explanation is the low percentage of the solar energy converted in the photo-synthesis (in the order of 0,5% of the solar radiation on a horizontal area in Denmark).

6.3. Different Fuels Different Roles

Since the results point to electric vehicles as the most efficient fuel cycle for renewable energy it would be tempting to follow this and only this option. Other considerations speak against this, though. First, it is always a hazardous strategy to place all bets on one horse. Secondly, the potential application of electrical vehicles are restricted by their limited range. Technological development probably will increase the range in coming years, but the range would have to be weighed out against other considerations (notably costs) and in any case there is a certain degree of uncertainty linked to the development (for instance, technical, economical and commercial risks). Probably the range for all practical purposes will be limited to some 300 kilometres.

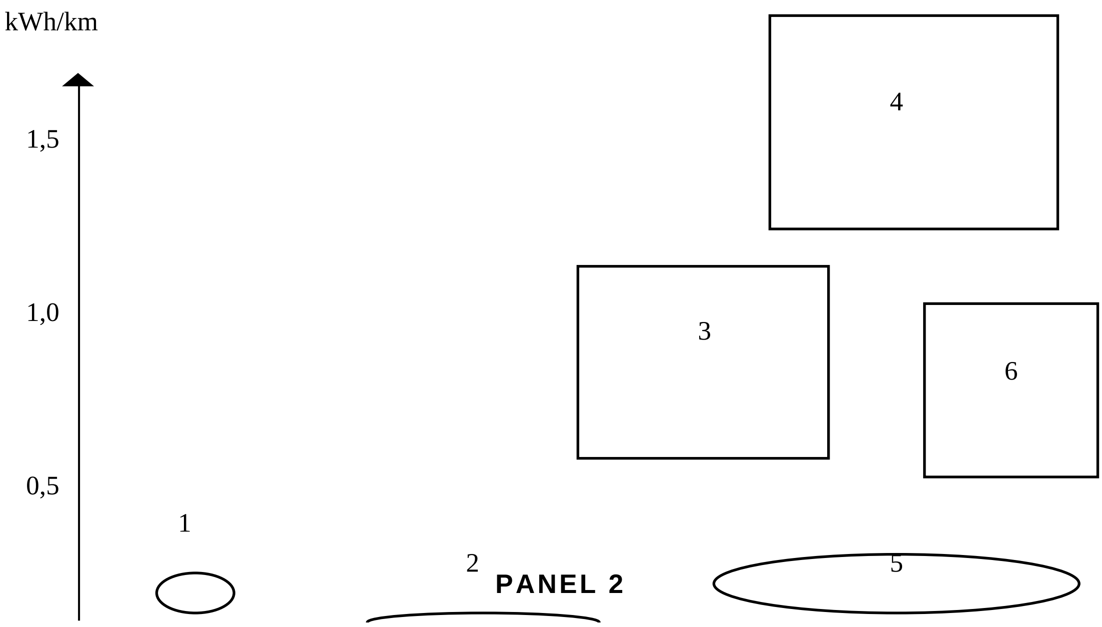

Figure 3. *Specific electricity consumption (kWh/km) versus range for different alternative fuel vehicles (Jorgensen 1998a; Jorgensen & Nielsen 1998). See text for explanation.*

100 500 Range (km) (km)

This would still leave a possible role for hydrogen for certain applications, as illustrated by Figure 3. This graph shows the specific electricity consumption (kWh electricity per km) and range (km) for different electric and hydrogen technologies. Electrical propulsion based on today's technological level (1) results in a very efficient fuel cycle but also limited range. Advanced electrical technology (2) may lead to considerably greater range and at the same time probably an even better fuel cycle efficiency, possibly leading to 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 ICE vehicles could increase ranges considerably but at the expense of the fuel cycle efficiency. In particular, liquid hydrogen (4) has very poor energy efficiency characteristics but also scope for very long ranges, whereas onboard storage in metal hydrides or as compressed gas (3) gives better fuel cycle efficiency and shorter range. Fuel cell technology combined with liquid hydrogen storage (6) or storage by means of metal hydride or compressed gas tank (5) would at the same time increase the range and improve fuel cycle efficiency.

7 - INTEGRATED APPROACH TO FUEL CYCLE EFFICIENCY IMPROVEMENTS

In this section, the potentials for fuel cycle efficiency improvements of integrated approaches, addressing the fuel cycle in its entirety (including other aspects of vehicle improvements than the drive train). A key issue is the time scale of the penetration of the efficiency improvements in the vehicle stock. Section 7.1 summarises a study of the time scale based on (Jorgensen 1998a) whereas the remainder of this section discusses to key issues in this context: the pro and cons of leapfrog technologies (Section 7.2) and the question of whether the efficiency improvements should be seen as a possibility or a probability (Section 7.3).

7.1. Efficiency Improvement Potentials

The theoretical potentials for improvement of the fuel cycle efficiency are substantial. The practical exploitation of these potentials depends on the costs as well as the technical and commercial risks one is prepared to take - and moreover there is a delay of the impact on energy use and CO2-emissions due to the time it takes to replace the vehicle stock (and frequently also to built up sales of the new technology).

Based on (Jorgensen 1998a) the improvement potentials for passenger cars can be characterised by means of different so-called Technology Levels (Lovins et al 1993; Nadis & MacKenzie 1993; DeCicco & Ross 1993; Moore & Lovins 1995):

- The Reference Level (REF) is the present vehicle stock average.

- Average Sold Technology Level (AST) represents the average of today’s vehicles, i.e. the level that the vehicle stock average is approaching if the present development continues.
- Best Sold Technology Level (BST) is based on the best technology currently available in the marketplace in Denmark and illustrating the maximum improvement potentials within the present market place.
- The Developed Technology Level (DEV) represents technologies that are close to commercialisation and do not face engineering constraints. There are, however, certain uncertainties due to limited experiences with large-scale production (manufacturing risks) and with the marketing of the improvements (commercial risks).
- The Efficient Technology Level (EFF) is based on improvements in advanced stages of development, albeit needing a certain technical development before being available for production, typically within about 10-15 years.
- The Hypercar Level (HYP) presumes the introduction of breakthrough technologies for both the vehicle as such and the drive systems (considered to be based on fuel cells). Because of this, many uncertainties are linked to this technological development.

Table 2 illustrates the estimated potentials for improvement of fuel economy of a medium-sized passenger car.

Tabel 2. Estimated improvement potentials for fuel economy of passenger cars for different Technology Levels (Jorgensen 1998a).

	FUEL ECONOMY	PRIMARY ENERGY USE	REDUCTION FROM REF
	km/litre gasoline equivalent	*MJ/km*	*%*
REF	13,5	2,7	0
AST	13,5	2,7	0
BST	18	2,0	25
DEV	19-21	1,8 - 1,9	30 - 35
EFF	33-40	1,0 - 1,1	60 - 65
HYP	65-80	0,45 - 0,55	80 - 90

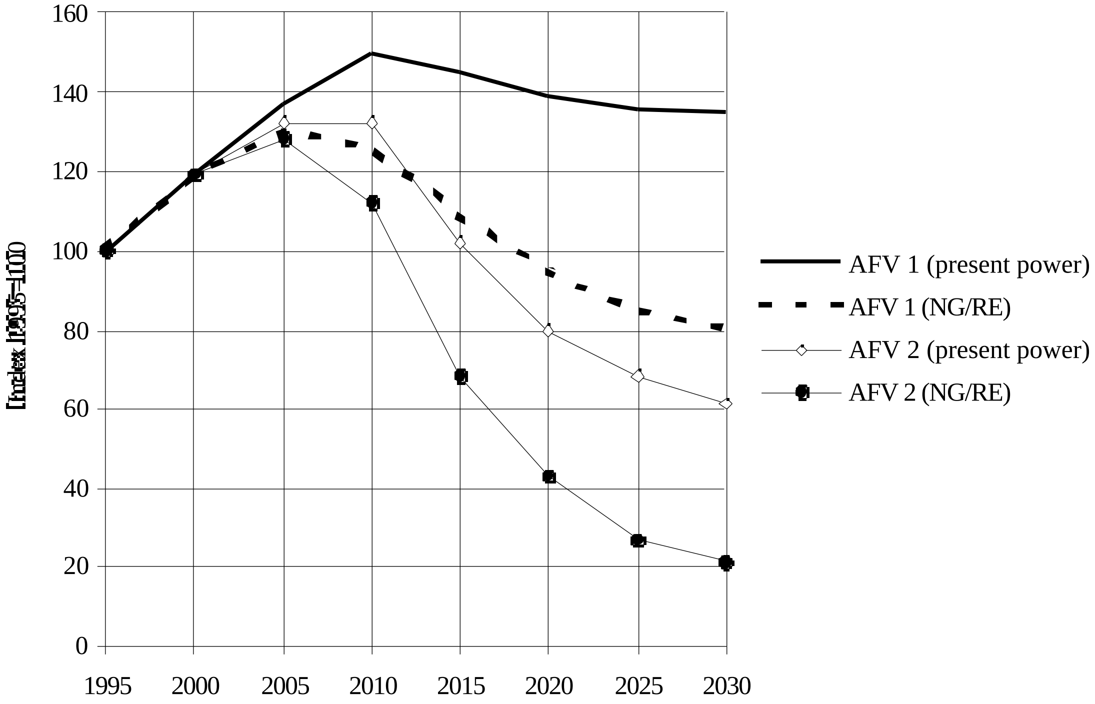

Figure 4. *Projected indexes for passenger car CO2-emissions for two different types of alternative fuel vehicles and different assumptions regarding power supply development (present power system and gradual shift to natural gas and renewable energy, NG/RE). Based on (Jorgensen 1998a).*

The delay of the effect of the technical improvements on transport sector CO2-emissions is illustrated by Figure 4 showing the projected development in the CO2-emissions of the total Danish stock of passenger cars for two alternative fuel vehicle scenarios (based on present power system as well as the projected power system in Energy 21, i.e. a gradual shift to natural gas and renewable energy). In this graph, *AFV1* is based on today's electrical vehicles, presuming a 50% penetration of the passenger car sale in the course of 10 years whereas AFV2 is consisting of AFV1 plus advanced electric vehicles and hydrogen fuelled fuel cell vehicles (both of which enter the market within 10 years).

The graph shows that technological improvements will take decades to penetrate the vehicle stock. Even the advanced alternative fuel vehicles (AFV2) will take about 15-20 years to offset the impact of the transport growth. And these scenarios presume that the technical improvements are used for improvement of the fuel economy only, i.e. that there is no increase in the vehicle standard. In any case, the technology improvements only have an major impact in the longer term.

7.2. Leapfrog Technologies or Incremental Development

Since the beginning of this century, nearly all vehicle design has been incremental refinements on existing designs whereas very few leapfrog developments - that is, designs breaking fundamentally with existing designs - have taken place (Groenewegen & Potter 1996; Lovins 1996; Maruo 1996). Automobile industries generally act very conservatively in the development process, reinforced by close competition between a relatively small number of large companies, which means that the competitors tend to follow each other very closely with regard to the options provided for the market (Fogelberg 1996; Maruo 1996).

Leapfrog technologies - explicitly or implicitly - play an important role in the debate on the scope for ecological and social sustainability, e.g. in conjunction with the debate on "Factor 4" and "Factor 10 improvements" (von Weizcäcker et al 1997; Goldemberg 1998). The leapfrog development can be seen as a necessity to enable the addressing of ecological and social demands on a global scale, but in addition there are several examples of analysts viewing the leapfrog development as a revolution in the making (Lovins et al 1993; Flavin & Lenssen 1995; Lovins 1996). The hypercar concept advanced by Amory Lovins is an example of the latter perception (see Section 3). Lovins attacks the claim of many analysts that the potentials for efficiency improvements has been exhausted, instead pointing to the opportunities in leapfrog technologies. Moreover, the automobile industry is criticised for focusing too much in drive system development. In contrast, leapfrog technologies should build on an integrated approach addressing both vehicle load and the drive system issues in the same process.

In Lovins' view, leapfrog technologies are needed not only to speed up the development but even to bring the efficiency improvements beyond a certain level. In this respect, he perceives the incremental approach - refinements of the existing vehicle technologies - is an obstacle to, rather than a step towards, major savings in the transport sector.

7.3. Efficiency Measures - Possibility or Probability

The technical improvements of the energy-efficiency of the automobile have not resulted in vehicles with a better fuel economy, since the improvements have been offset by heavier and more powerful cars, increases in the provision of air conditioning etc. (Jorgensen 1998b). Therefore, it is tempting to promote renewable fuels - or other fuels with low CO2 emissions per energy content - instead of addressing the issue of reducing the energy use at the end use level. Renewable fuels, however, are not without problems and should not be perceived as an unlimited source of energy. The potentials of biofuels are limited due to their excessive land requirements. Electric and hydrogen vehicles offer mush more efficient fuel cycles, but their large-scale application is a long-term option, requiring not only technological development but also the surmounting of opposition with regard to user perception, infrastructure etc.

Hence, it is crucial to maintain and reinforce the efforts to improvement the fuel efficiency. In this context, the hypercar serves an important role in pointing to the potentials for major efficiency improvements that should be applied before embarking on major shifts to renewable fuels. These improvements, however, are seen by Amory Lovins not only as a possibility but as an “emerging revolution” (Lovins 1995), implying that the development of the leapfrog technologies is bound to happen and, indeed, is in the process of doing so.

While there are examples of such leapfrog technologies gaining progress, the RMI analysts generally do not document that there is an ongoing revolution. In particular, the anticipation of vehicles with substantially improved fuel economy while competing with the present automobile in every sense (including costs) is not borne out in practice. The major example of a leapfrog technology for the transport sector may be the development of fuel cells for mobile applications (Fuel Cell Technical Advisory Panel 1998). If automobile manufacturers decide to go ahead with implementation of fuel cell drive systems in automobiles, this probably will take the form of methanol or gasoline drive fuel cell vehicles - which would lead to much more limited environmental improvements than would be the case for hydrogen fuel cell vehicles. In addition, even the most optimistic scenarios only envisage the annual manufacturing of a few hundred thousands FC vehicles within the next decade - which means that more than 95% of the vehicle production is set to be conventional ICE models.

8 - CONCLUSIONS - IS TECHNOLOGY THE SOLUTION?

Fuels based on renewable sources offer potentials for both improved fuel cycle efficiency and reduced CO2-emissions. Renewable fuels based on electrical or hydrogen propulsion offer the greatest potentials, though generally with a longer time horizon. However, these fuels do not substitute other transport planning measures, and in particular they do not substitute the need to curb the growth in transport demand and motor vehicle driving.

First, renewable fuels are not unlimited and certainly not without problems. Therefore, any effort to promote these fuels should be combined with measures to increase the fuel cycle efficiency as well as to end the transport demand growth (the sufficiency issue). To accomplish the potentials for substantial efficiency improvements it is vital that effort to improve the vehicle efficiency addresses both vehicle load and drive system issues rather than fitting new drive trains (e.g. fuel cell based) in otherwise conventional vehicles. As the penetration of the vehicle stock of technical improvements generally is slow, there is a particular need to curb the transport demand in the near term in order to win time for technological improvements to work.

Secondly, many problems are linked to transport and traffic (motor vehicle driving) and therefore there is a need to reduce vehicle use, regardless of how clean the energy is. For instance, congestion and the physical structures are linked to the level of traffic and the motorised transport (mobility) as such influences many socio-economic structures (e.g. the provision of retail shops and the shaping of everyday life). In isolation, the provision of "clean energy" for fuel-efficient motor vehicles may worsen these problems rather than relieve them (especially if fuel prices are not increased as fuel economy standards are improved. In an overall strategy for sustainable transport, on the other hand, renewable fuels may enlarge the manoeuvring space for the different considerations. This can be used in a back-casting process where assessments of carrying capacity and technological improvement potentials are use as basis for evaluation of the ecological space for transport, cf. (Steen et al 1996).

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