Pergamon

Energy 26 (2001) 973–989

ENERGY

www.elsevier.com/locate/energy

Primary energy efficiency of alternative powertrains in vehicles

Max Åhman *

Department of Environmental and Energy Systems Studies, Lund University, Gerdagatan 13, SE-223 63, Lund, Sweden

Received 23 June 2000

Abstract

This study considers the technical potential concerning the energy efficiency attainable for vehicles with alternative powertrains within 10–20 years. The potential for electric vehicles (BEVs), hybrid electric vehicles (HEVs) and fuel-cell electric vehicles (FCEVs) is assessed and compared with the potential improvement in conventional vehicles with internal combustion engines (ICEVs). Primary energy efficiency is the measure used in this study for comparison. The calculations of primary energy efficiency are based on three different resources: fossil fuels, biomass, and primary electricity from wind, solar or hydropower. This study shows that there is potential for doubling the primary energy efficiency using alternative powertrains in vehicles such as BEVs, HEVs and FCEVs, compared with existing ICEVs. All vehicles with an alternative powertrain have a higher potential for primary energy efficiency than vehicles with an improved conventional powertrain. No "winner" amongst the alternative powertrains could be identified from a primary energy efficiency point of view. © 2001 Elsevier Science Ltd. All rights reserved.

---

1. Introduction

Road traffic causes a number of environmental problems such as noise, congestion, and the emission of NO_x, CO, CO_2, and particulate matter. According to a number of "business as usual" prognoses, the growth in the demand for transport is expected to continue, which will exacerbate the negative impact on the environment, see, for example [1,2].

The perhaps most difficult environmental problem to solve is the expected greenhouse effect, caused primarily by the emission of CO_2. Technical innovations, such as the catalytic converter and improved fuels, have decreased the emission of VOC, NO_x, SO_x, and lead due to road trans-

---

* Tel.: +46-222-86-43; fax: +46-222-86-44.
E-mail address: max.ahman@miljo.lth.se (M. Åhman).

0360-5442/01/$ - see front matter © 2001 Elsevier Science Ltd. All rights reserved.
PII: S0360-5442(01)00049-4

port during the last 15 years while the limited improvement in vehicle fuel economy has been offset by a growing demand for transportation [3].

A long-term solution for mitigating CO_2 emission in the transport sector would be the use of renewable fuels instead of fossil fuels. Fuels and electricity from renewable sources are, however, still relatively expensive and the supply is limited [4]. Even in optimistic scenarios the renewable energy supply will be restricted [5]. The use of more energy-efficient vehicles is an important step towards a technical solution of the CO_2 problem. Several new energy-efficient powertrains are currently being investigated by scientists, governments, and car manufacturers.

The aim of this study was to assess the future possible primary energy efficiency attainable in passenger cars with alternative powertrains. To be able to compare the system efficiency of vehicles that use different energy carriers, the primary energy efficiency was used as a measure for comparison. Primary energy efficiency takes into account all energy use “from the well to the wheel”. The primary energy efficiency for energy chains based on fossil fuels, biomass, and primary electricity from renewable sources, was compared in this study. Future efficiencies stated in this study are assumed attainable if developments of key technologies are successful and energy efficiency has high priority in development.

Other studies have compared alternative powertrains with conventional vehicles and analysed the potential benefits regarding energy efficiency. Most of these studies, however, have compared only one of the alternatives with the conventional powertrain. In Ecotraffic, Metz et al., Wang and Deluchi, OECD/IEA, and Wabro and Wagner [6–10] the battery-powered electric vehicle (BEV) is compared with the internal combustion vehicle (ICEV). The hybrid electric vehicle (HEV) and the fuel-cell vehicle (FCEV) are compared with the conventional ICEV in Amann, Cuddy and Wipke, Wang et al. [11–13] and in Lipman and DeLucchi [14], respectively.

When comparing powertrains using the same energy carrier (such as petrol) there is no need to consider the primary energy efficiency [11,12]. When different energy carriers with varying degrees of energy losses during fuel production and distribution are used, primary energy efficiency analysis becomes necessary [6–8]. Some studies do not include renewable fuels in their assessments [7] and other studies do not include all the alternative powertrains relevant today in the comparison [6,8,14].

In this study, we focused on primary energy efficiency both from fossil and renewable resources, and we included all of the currently most promising alternative powertrains. Another important feature is that the future potential for all the different vehicle types and energy conversion methods was investigated. This study does not show which energy efficiency *will* be attained in the future but which energy efficiency *could* be attained.

2. Method

The powertrains studied included electric drivetrains[1] in BEVs, HEVs with an internal combustion engine (ICE) and in FCEVs. These vehicles are probable future alternatives to conventional

---

[1] The term drivetrain typically refers to the transmission system from engine output shaft to driven road wheels. In the term alternative powertrain we include both the electric drivetrain, energy storage (e.g. batteries and hydrogen storage), and, possibly, a prime mover (ICE or fuel-cell).

ICEVs. The focus of the study was on powertrain technology potentially available within 10–20 years. The time scale was set to enable an assessment of potential without considering the time needed for the development of different powertrains. The future development of the ICEV was also assessed and compared with the alternative powertrains.

The calculations of primary energy efficiency were based on three different resources: fossil fuels, biomass and primary electricity from wind, solar or hydropower. The definitions of powertrain efficiency, vehicle efficiency and primary energy efficiency are shown in Fig. 1. W_D is the primary energy, W_C is the energy supplied to the vehicle, W_B is the energy supplied to the powertrain, and W_A is the useful energy at the wheels.

Powertrain efficiency, $\eta_{\text{powertrain}}=W_A/W_B$

Vehicle efficiency, $\eta_{\text{vehicle}}=W_A/W_C$

Primary energy efficiency, $\eta_{\text{primary}}=W_A/W_D$.

The *powertrain efficiency* was calculated from the efficiencies of the different components included in the powertrain. The component efficiencies are assumed future mean efficiencies attainable over a normal drive schedule. To calculate the *vehicle efficiency*, the powertrain efficiency was corrected for losses due to the power required for heating and for the benefits when no energy is required during idling and the use of regenerative braking. The *primary energy efficiency* included the energy used for energy extraction, conversion, distribution and storage. The energy embodied in plants, buildings and vehicles was not included. Embodied energy typically accounts for only 7–8% of total life-cycle energy use today [52]. However, for future fuel efficient vehicles this fraction could increase to between 14 and 18% for the different alternatives in this study [52]. For electricity, a marginal perspective was used, which means that the efficiency of the electricity supply was calculated as the efficiency of the supplementary electricity production required by the system to supply the energy for the vehicles.

The alternative vehicles are assumed to have the same comfort, performance, and size as a

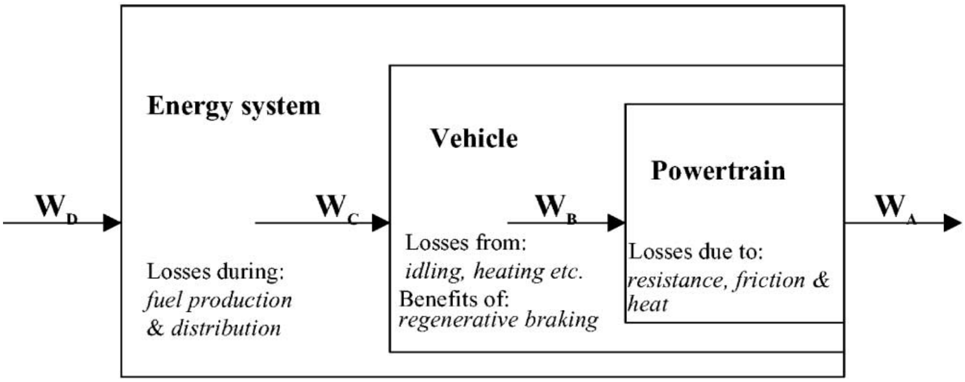

Fig. 1. Definitions of primary energy efficiency, vehicle efficiency, and powertrain efficiency.

conventional vehicle today. Looking at efficiency will, however, not give all the answers as the future weight may differ between the alternatives (notably for the BEV). The potential for further efficiency improvement by reducing vehicle weight, rolling resistance and aerodynamic drag is discussed in Section 5.

3. Description of technologies

3.1. ICEVs with a conventional powertrain

The conventional powertrain consists of a fuel tank, an internal combustion engine, and a transmission. A characteristic of the internal combustion engine is that maximum efficiency is attained near the maximum load point. This makes the mean efficiency relatively low since maximum power is very seldom used under normal driving conditions. The mean power required in a US Federal Test Procedure (FTP) schedule is below 10 kW [15], while the maximum power required is between 60 and 90 kW, depending on the size of the vehicle. The mean efficiency is thus low, around 18% in an FTP schedule [6], compared with the maximum efficiency, which is between 35 and 40% in a new engine today. Possible options for improving the mean efficiency in the conventional powertrain are variable valve timing, shut-off during idling, higher compression ratio and a continuously variable transmission, see [16].

3.2. The electric drivetrain and BEVs

The electric drivetrain is an essential part of BEVs, HEVs, and FCEVs and consists of a generator, an electric motor, and a transmission.

The battery has always been the weak link in BEVs. Low energy storage capacity compared with petrol has restricted the driving range of BEVs. A battery in a BEV should store up to 30 kWh to afford the vehicle an acceptable range. In order to make BEVs commercially viable, the United States Advanced Battery Consortium (USABC) argues that a BEV battery should be able to store at least 150 Wh/kg [17]. The batteries used today are lead/acid (Pb/A), nickel–metal hydride (NiMH), and lithium batteries which store 80–100 Wh/kg [18]. The only battery believed to have the long-term potential to reach the USABC goal of 150 Wh/kg, is the lithium–polymer battery, see, for example [18,19].

The cost of batteries is a major obstacle today. A NiMH battery costs somewhere between 200 and 350 US$/kWh [18], which means between 6000 and 10 500 US$ for a BEV battery package of 30 kWh. The only battery expected to be able to attain the long-term goal set up by the USABC (a cost of $<$150 US$/kWh) is the Pb/A battery [18,20]. Some analysts argue, however, that the lithium–polymer battery may also have the long-term potential to reach a cost close to 150 US$/kWh [18].

Pb/A batteries have been the dominating type of batteries in BEVs and HEVs so far, but the future BEVs in this study are assumed to have a NiMH or lithium battery. Both batteries are available today, but they differ in price and availability in favour of the NiMH battery. For future HEVs, Pb/A batteries might well prove to be the best alternative in the medium term, considering both technical performance and price [18].

Both generators and electric motors have been greatly improved during the past 20 years. Due to the development of advanced electronic control systems, the mean energy efficiency over a normal drive schedule has increased both for generators and electric motors, see, for example [21–23]. Today, only a one-speed reduction-gear is needed to manage all possible power and speed requirements for an electric motor with an advanced control system [21–23]. The general assumption of this paper is that the variations in load and speed will, to the greatest extent possible, be handled by the electric drivetrain.

The potential energy efficiency of an electric drivetrain ranges between 65 and 75% (see Table 1). Current efficiencies are lower, around 57%. Future improvements in efficiency will result from the implementation of an advanced control system together with a modern generator and electric motor. The use of lithium–polymer batteries could also improve the electric drivetrain efficiency substantially in the future. The electric drivetrain in HEVs may be more efficient than in BEVs due to the potential for more efficient batteries.[2]

Table 1
Assumed future possible component mean efficiencies over a normal drive schedule for the electric drivetrain

Electric drivetrain in the following configurations	Generator (%)	Battery (%)	Electric motor and control system (%)	Transmission (%)	Total energy efficiency for the drivetrain (%)[h]
BEV (NiMH battery) today	85[a]	80[a]	86[b]	98[g]	57
BEV (NiMH battery) potential	92[b]	81[c]	89[f]	98[g]	65
HEV (Pb/A battery) potential	92[b]	90[d]	89[f]	98[g]	72
BEV/HEV (Li battery) potential	92[b]	95[e]	89[f]	98[g]	76

[a] The efficiencies of vehicles on the market today differ widely between manufacturers due to rapid development. Assumptions based on [9,24].

[b] Assumption based on: [25].

[c] Assumption based on [18,26].

[d] Pb/A batteries, which are efficient and easy to use in HEVs [12,18].

[e] The performance of lithium–polymer batteries is difficult to validate because there is basically only one advanced manufacturer, 3M/Hydro-Quebec. Adapted from [19,27,28].

[f] Assumptions based on [21–23].

[g] Assumed mean efficiency of a reduction gear. Based on: [9,12]. A reduction gear is also assumed in the electric drivetrain in parallel HEVs in the future.

[h] Multiplying these mean efficiencies is a simplification for calculating the system mean efficiency, but given the uncertainties the figures represent good indicators on future possible mean efficiency.

---

[2] Hybrid vehicles can use lead/acid batteries. Such batteries are very efficient if not charged to 100% [18].

3.3. HEVs with internal combustion engines

In the hybrid powertrain, an electric motor and a battery are combined with a heat engine and a fuel tank. The heat engine, *primary engine*, can charge the battery, or take over the driving from the electric drivetrain when the battery is discharged.

The primary engine and the electric drivetrain are either used in series or in parallel. In a series configuration, all the energy must go through the electric drivetrain. In a parallel configuration, part of the energy passes a mechanical drivetrain. The HEVs sold today are not pure series or parallel configurations, but have increasingly integrated configurations.

Today, ICEs dominate as primary engines, see, for example Toyota Prius and Honda Insight. With hybridisation, the ICE can be designed for the mean power of a normal driving schedule instead of the maximum power required. This allows the engine to operate closer to its maximum efficiency. We have not considered gas turbines or Stirling engines, as the potential for high energy efficiency in passenger-car-sized engines seems to be low, see, for example [29,30].

The mean efficiency of the ICE in a hybrid configuration is given in Table 2. The ICE usually used is a four-stroke direct injection (4SDI) engine, and the assumed ICE developed for future use is either a compression ignition direct injection (CIDI) engine or a new engine type, combining both CIDI and 4SDI features, e.g. the active thermal atmospheric combustion (ATAC) engine. The parallel configuration assumed in this study is a genuine parallel configuration with as small a battery pack as possible.

3.4. FCEVs

Fuel-cell technology is now being developed for automotive purposes. The most interesting fuel cell for this application today is the proton exchange membrane (PEM) fuel cell. The advantage of the fuel cell is the potential for high energy efficiency and zero tail pipe pollutants.

One disadvantage of the fuel-cell system is the requirement of pure hydrogen for fuel in the cell. Hydrogen can be stored on board the vehicle, either as a liquid, in nanofibres or in hydrides, or as compressed gas. Nanofibre technology is still at the basic research level and was not considered in this study. Liquid storage is the most energy-consuming alternative. About 50% of the energy content is used to liquefy the hydrogen gas [4,31,32]. The energy efficiency of compressing

Table 2
Assumptions of mean primary engine energy efficiency in different configurations

Mean engine efficiency over a normal drive schedule	HEV series configuration (%)	HEV parallel configuration (%)	ICEV (%)
ICE, today (4SDI)	–	–	18[a]
ICE, future (CIDI or developed 4SDI)	40[b]	36[b]	24[c]

[a] Efficiency today. Adopted from [6].

[b] Adapted from [12] assuming a diesel engine with 43% maximum efficiency and a 55%FUDS/45%FHDS. The parallel engine will have to deal with greater variation in load and thus have a lower mean efficiency than the series hybrid. Future engines will probably have the same efficiency, even if they are of another type (e.g. ATAC, 4SDI, GDI).

[c] Adapted from [16] assuming variable valve timing, idle shut-off, higher compression ratio, etc.

hydrogen gas to 350 bars is about 70–90%[3] [35]. Another alternative is to use a "hydrogen carrier", e.g. methanol or petrol, to provide the hydrogen for the cell. Methanol and petrol are easy to store with normal vehicle technology, but this solution lowers the fuel-cell system efficiency (see Table 3).

A fuel cell using methanol directly, without reforming it to hydrogen, is still in a very early phase of development [36,37], and was thus not considered here.

The PEM fuel cell has different efficiency features compared with the ICE, making hybridisation less interesting. The maximum efficiency of a fuel cell is attained at 25–50% of maximum load [38], which gives no benefit from reducing maximum power with hybridisation. However, there are other advantages in hybridisation of fuel-cell systems. The most obvious ones are the possibility to use electricity from the battery during idling and to help FCEVs to start cold, and the possibility of utilising regenerative braking [39,40].

In this study, hybridisation of the fuel-cell vehicle was assumed and the fuel cell was assumed to be as small as possible due its high cost. This makes the efficiency lower than the maximum possible. Other strategies may, however, be chosen by industry, see, the discussion in [40]. Assumptions regarding the efficiency of a PEM fuel-cell system are given in Table 3.

4. Efficiencies of different powertrains

Calculated efficiencies for the powertrains studied are given in Table 4. The highest efficiency is achieved for the battery-powered electric vehicle. The two hybrid powertrains and the fuel-cell powertrain fuelled with methanol have approximately the same efficiency. The fuel-cell powertrain has about 20% higher efficiency when fuelled with pure hydrogen gas than when it is fuelled with methanol. Furthermore, there is a considerable potential for improvement in the conventional powertrain.

The electric drivetrain offers the benefits of no fuel use during idling and the possible use of regenerative braking. But there is also a disadvantage in that electric power is needed for heating, since the heat loss from the ICE are too small to cover the demand for interior heating of the

Table 3
Assumed future PEM fuel-cell system mean efficiency

Mean fuel efficiency, hybrid configuration	Hydrogen gaseous (%)	Hydrogen liquid (%)	Methanol (%)	Petrol (%)
PEM fuel-cell system[a]	47	47	47	47
Reformer efficiency[b]	–	–	85	80
Total fuel-cell system energy efficiency	47	47	40	38

[a] Adapted from [27,30,39] with an assumed maximum efficiency of 55% and the efficiency curve in [40].
[b] Adopted from [30].

---

[3] With figures from [33], the energy efficiency is 73% assuming compression from 7 to 35 MPa. DeLuchi and Ogden claim a higher efficiency, 91% [34]. The figures are uncertain and depend partly on the assumptions regarding electricity generation.

Table 4
Future powertrain efficiencies

Powertrain efficiency	Primary engine (%)[a]	5-speed transmission (%)	Electric drivetrain (%)[b]	Total powertrain energy efficiency (%)
Battery-powered powertrain	–	–	65	65
Hybrid powertrain parallel	36	92	68[c]	30[d]
Hybrid powertrain series	40	–	72	29
Fuel cell powertrain methanol fuelled	40	–	72	29
Fuel cell powertrain hydrogen fuelled	47	–	72	34
Conventional developed	24	92	–	22
Conventional today	18	92	–	16

[a] Based on Table 2.

[b] Based on Table 1.

[c] Adapted from Table 1 with the exception that the transmission is assumed to be mechanical.

[d] Assuming a 55% city driving schedule with electric drivetrain and 45% highway driving schedule with mechanic drivetrain.

vehicle. All these features influence the total vehicle efficiency (see Table 5). To calculate the effects on vehicle efficiency, the energy sinks for braking, idling and heating were estimated according to Amann [11] and DeCicco and Ross [16]. The difference between vehicle and powertrain efficiency is small, but a small relative improvement for vehicles using electric drivetrains compared with vehicles using conventional powertrains can be identified (see Table 5).

The primary energy efficiencies, when energy carriers based on fossil resources are used, are given in Table 6. The fossil fuels are produced from crude oil or natural gas. Marginal fossil-based electricity generation from coal was assumed in the short term and, in the long term, new marginal electricity from natural-gas plants was assumed. The reason for this is that power from new natural-gas plants is produced at a lower cost than in new coal-fired plants [41].

With new electricity production, based on natural gas, the BEV has the highest primary energy efficiency of the alternatives studied. The advantage with regard to the emission of CO_2 is even higher due to lower carbon content per unit energy than in coal or oil. If the electricity is generated from coal, the primary energy efficiency for BEVs is lower than for HEVs and FCEVs.

HEVs with advanced heat engines are twice as efficient as conventional vehicles today. FCEVs have lower efficiencies than HEVs due to high conversion losses from natural gas to hydrogen or methanol.

An important option for CO_2 mitigation is the use of biomass as a renewable energy source [41]. The primary energy efficiencies for vehicles using energy carriers based on biomass are given in Table 7. The BEV has the highest potential for primary energy efficiency. One reason for this, apart from the high vehicle efficiency, is the fact that liquid and gaseous fuels are produced from biomass with relatively low efficiency. The various HEVs and FCEVs all have similar efficiencies.

Finally, the primary energy efficiencies for vehicles using primary electricity from solar, wind,

Table 5
Vehicle efficiency calculated as consumed energy at the wheels divided by the total energy supply to vehicle, see Fig. 1

Vehicle	Consumed energy at the wheels	Energy out from powertrain[a]	Energy to powertrain[b]	Energy used for extra loads[c]	Energy during idling[d]	Total energy supplied to vehicle	Vehicle efficiency[f] (%)
BEV	100	95	146	17	0	163	61
HEV parallel	100	95	327	14	0	340	29
HEV series	100	95	327	14	0	340	29
FCEV methanol	100	95	327	14	0	340	29
FCEV hydrogen	100	95	279	14	0	293	34
ICEV developed	100	100	452	10	27[e]	489	20
ICEV today	100	100	625	10	75	700	14

[a] 5% of consumed energy at the wheels is saved due to regenerative braking which assumes that 25% of the braking energy is regenerated. This relatively low figure is due to traffic safety.

[b] Calculated as (energy out from powertrain)/(powertrain efficiency based on Table 4).

[c] Assumed to be 10% of the useful energy at the wheels according to [16]. Consideration taken of the fact that some heat losses can be used for heating for the FCEV and the HEV.

[d] Energy during idling assumed to be 12% of “energy to powertrain”. Adapted from [11,16].

[e] 50% of energy used during idling can be saved, according to [16].

[f] Calculated as (consumed energy at the wheels)/(total energy supplied to vehicle).

Table 6
Primary energy efficiency with a fossil primary energy source

Vehicle	Primary energy	Energy carrier	Primary energy to energy carrier[a] (%)	Distribution[b] (%)	Vehicle efficiency[e] (%)	Primary energy efficiency
BEV	Coal today	Electricity	40[c]	93	61	23
BEV	Natural gas future	Electricity	55[d]	93	61	31
HEV parallel	Crude oil	Diesel	95.3	99.8	30	28
HEV series	Crude oil	Diesel	95.3	99.8	29	28
FCEV	Natural gas	Hydrogen (350 bar)	85	86	34	25
FCEV	Natural gas	Methanol	72	99.6	29	21
ICEV developed	Crude oil	Petrol	91.5	99.8	20	19
ICEV today	Crude oil	Petrol	91.5	99.8	14	13

[a] Adopted from [42,43].

[b] Adopted from [42,43].

[c] Relates to Danish coal power with an efficiency ranging between 36% and 47%.

[d] Adopted from [44].

[e] From Table 5.

Table 7
Primary energy efficiency with biomass as primary energy source

Vehicle	Primary energy	Energy carrier	Primary energy to energy carrier[a,b] (%)	Distribution/ storage[c] (%)	Vehicle efficiency[f] (%)	Primary energy efficiency (%)
BEV	Biomass	Electricity	45[c]	93	61	25
HEV parallel	Biomass	Methanol	63	99.6	30	19
HEV series	Biomass	Methanol	63	99.6	29	18
FCEV	Biomass	Hydrogen (350 bar)	69	86	34	20
FCEV	Biomass	Methanol	63	99.6	29	18
ICEV developed	Biomass	Methanol	63	99.6	22[d]	14
ICEV today	Biomass	Methanol	63	99.6	15[e]	10

[a] Adopted from [42,43].
[b] Adopted from [45].
[c] Adopted from [42,43].
[d] Efficiency is assumed to be 10% higher than for petrol. Source: [46].
[e] Efficiency is assumed to be 6% higher than for petrol. Source: [46].
[f] From Table 5.

or hydro power are given in Table 8. In this case, only BEVs and FCEVs were considered. Hydrogen for the fuel cell is produced through the electrolysis of water. The efficiency of producing primary electricity is set to 100% for all the alternatives.

There is a substantial energy loss when converting electricity to hydrogen and back to electricity again in the FCEV. For this reason, the most efficient alternative would be to use the electricity directly in a BEV. Hydrogen is, however, easier to store than electricity and in a long-term scenario, using solar power, hydrogen might be the safest and most practical energy carrier.

Table 8
Primary energy efficiency with solar, wind or hydropower as primary energy source

Vehicle	Primary energy	Energy carrier	Primary energy to energy carrier (%)	Distribution/ storage (%)	Vehicle efficiency[d] (%)	Primary energy efficiency (%)
BEV	Solar, wind or hydropower	Electricity	100	93[a]	61	57
FCEV	Solar, wind or hydropower	Hydrogen (350 bar)	90[c]	86[b]	34	26

[a] Adopted from [43].
[b] Adopted from [42].
[c] Adopted from Ogden and Nitsch [47] who assumed that the efficiency today (1994) of 70–75% can be increased to 85–90% in the future.
[d] From Table 5.

4.1. Sensitivity analysis

The results presented above are based on a number of assumptions regarding the future energy efficiency of components in the powertrain and the possibility to integrate them with continued high mean efficiency over a normal drive schedule. This makes the conclusions sensitive to uncertainties regarding the successful development of components and control techniques for the electric drivetrain. The most speculative component assumptions that influence the future potential are associated with batteries and fuel cells, but assumptions regarding the development of ICEs could also be uncertain. The possibility for the electric drivetrain to handle load variations with the assumed high mean efficiency is also a crucial assumption. Different advances in development regarding the efficiencies of the most important and uncertain components are given as best, assumed, or worst cases in Table 9.

The effects on primary efficiencies, calculated with the highest and lowest component efficiencies in Table 9 for each powertrain, are shown in Fig. 2. The results in the figure are based on primary energy from biomass.

For the conventional powertrain, no further development of the current status is assumed in the worst case. The best possible development for an ICEV is equal to the assumed potential given in Table 8, since no further improvement beyond this level seems likely today. For all alternative powertrains, the development of a highly efficient electric drivetrain is crucial. The best possible development for the BEV is based on an optimistic potential for a 95% efficient lithium–polymer battery. For the HEV, the development of higher efficiency for small diesel engines is important, and for the FCEV, of course, the development of the fuel cell itself.

The conclusions that can be drawn from Fig. 2 are that the uncertainty in component development will not change the fact that ICEVs have the lowest potential for primary energy efficiency and BEVs have the highest potential, regardless of the assumptions made concerning component development as long as they are reasonable. The difference between alternative and conventional powertrains could, however, be smaller if the electric drivetrain proves less efficient than assumed. The relationship between HEVs and FCEVs could also change with different assumptions. All

Table 9
Different advances in development regarding energy efficiency of powertrain components

Uncertainty about future efficiency	Best possible efficiency (%)	Assumed efficiency (%)	Worst possible efficiency (%)
Electric drivetrain[a]			
BEV	76	65	57
HEV and FCEV	76	72	64
Fuel cells[b]	48	47	42
ICEs[c]	42	40	35

[a] Best possible development includes a lithium–polymer battery. The “assumed and worst possible mean efficiencies” are both for BEV (65 and 57%) and for a HEV (72 and 64%).

[b] The assumed fuel cell efficiency is optimistic, but possible in the long term. Not much potential above that assumed is considered possible.

[c] High efficiency ICEs are available today. Incremental improvements can be made upon the assumed efficiency, but not much more.

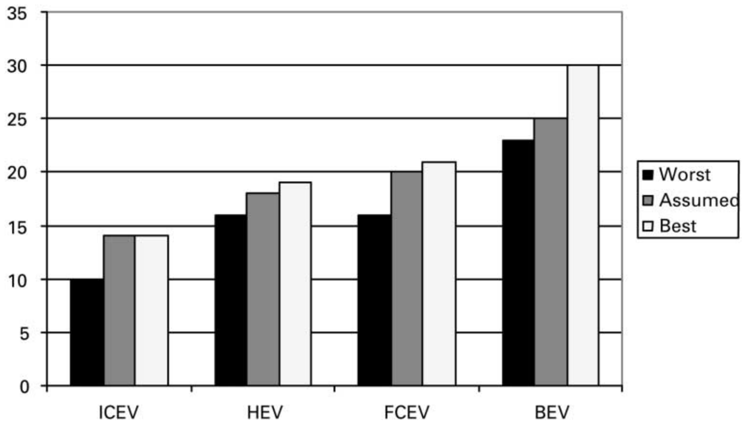

Fig. 2. The effects of uncertainty in component development on primary energy efficiency. Calculations were made assuming the primary energy to be based on biomass.

the selected components can develop independently, but links exist between components used in the lithium–polymer batteries and in the PEM fuel-cell system. Development of the conventional powertrain will have positive effects on the potential of the HEV, since the ICE is used in both hybrid and conventional powertrains.

5. Other means of reducing energy use in future vehicles

Reducing weight, rolling resistance, and aerodynamic drag can also play a major part in improving the energy efficiency of passenger cars. The effects of such measures are briefly discussed here. The importance of different measures in reducing energy use is given in Table 10. The division between the three different road loads is assumed to be one third each of the total road load, based on Amann [11] and DeCicco and Ross [16].

Apart from vehicle technology, energy use also depends strongly on vehicle speed. Rolling resistance is proportional to speed, the energy invested in kinetic energy is proportional to the square of the speed, and the aerodynamic drag is proportional to the cube of the speed. This means that a reduction in speed of 1% would give a theoretical reduction in driving energy (road load) of 1.98% (see Table 10).

Table 10
Changes in total energy use for vehicles as a result of changes in speed, weight, rolling resistance, and aerodynamic drag

Effect of road-load factors on total energy use	Speed. 1% reduction gives:	Weight. 1% reduction gives:	Rolling coefficient. 1% reduction gives:	Drag coefficient. 1% reduction gives:
Rolling resistance	1% reduction	1% reduction	1% reduction	No reduction
Aerodynamic drag	2.97% reduction	No reduction	No reduction	1% reduction
Kinetic energy (braking)	1.98% reduction	1% reduction	No reduction	No reduction
Total road load (theoretical)	1.98% reduction	0.66% reduction	0.33% reduction	0.33% reduction

Considering the medium-term scope for improvements in road load factors, the total road load can be reduced by 36% for future ICEVs compared with standard ICEVs today (see Table 11). For electric drivetrains the scope is less, 22% for a BEV and 29% for a HEV, due to the heavy batteries. Note that the reductions in road load are assumed to be introduced while preserving both the comfort and performance of the vehicle. Much larger reductions in road load might be possible in the longer term, see, for example [48].

6. Total potential reductions in primary energy use

Based on the road–load reductions given in Table 11, and the primary energy efficiency improvement given in Table 7, the total potential in percent, to reduce primary energy use can be calculated according to Eq. (1):

$$\Delta W_{\mathrm{T}}=(100-\Delta W_{\mathrm{RL}})\times\eta_{\mathrm{c}}/\eta_{\mathrm{n}} \tag{1}$$

where ΔW_{RL} (%) is the potential for reducing the road load (see Table 11). η_{c} is the primary energy efficiency for conventional vehicles today, and η_{n} is the primary energy efficiency for vehicles with alternative powertrains (see Table 7).

A combination of improved powertrain efficiency and reduced vehicle road load would enable future BEVs to run on only 38% of the fossil primary energy of a conventional vehicle today.

Table 11
The road-load factors today and the medium-term scope for improvements

Energy use	Today	Medium-term potential	Potential change	Impact of potential change on road load
Weight	1400 kg			
BEV		1300 kg[a]	−7%	−5%
FCEV		1200 kg[b]	−14%	−9%
HEV		1150 kg[c]	−18%	−12%
ICEV		1000 kg[d]	−29%	−19%
Rolling resistance	0.011	0.008[e]	−27%	−8.9%
Aerodynamic drag	0.4	0.3[f]	−25%	−8.25%
Total reduction of road load				
BEV				−22%
FCEV				−26%
HEV				−29%
ICEV				−36%

[a] Assuming a general weight reduction to 1000 kg+300 kg battery. Adopted from [18,30].

[b] Assuming a general weight reduction to 1000 kg+200 kg extra for fuel cell and battery. Adopted from [18,30].

[c] Assuming a general weight reduction to 1000 kg+150 kg extra battery. Adopted from [18,30].

[d] Assuming a general weight reduction to 1000 kg. Adopted from [30].

[e] A reduction down to 0.0085–0.0065 is possible, according to [12,16]. The Partnership for a New Generation of Vehicles (PNGV) hopes to reduce rolling resistance by 20% compared with a standard car today [11].

[f] A reduction of aerodynamic drag affects the appearance of the vehicle, hence the scope of improvement is limited. PNGV hopes to reduce aerodynamic drag by 20% compared with a standard car today [11].

Future HEVs would require 37%, FCEVs 40%, and the developed ICEV 45% of the primary energy consumed compared with an ICEV today.

The PNGV aims at developing a future vehicle that uses only 34%[4] of the fuel consumed in a standard car today. In this study, the total potential to reduce vehicle fuel consumption was calculated for the HEV and FCEV fuelled with petrol or methanol [Eq. (2)].

$$\Delta W_F=(100-\Delta W_{RL})\times\eta_{c2}/\eta_{n2}, \tag{2}$$

where ΔW_F is the total reduced vehicle fuel consumption and the vehicle efficiency of an ICEV today (η_{c2}) and the vehicle efficiency of a HEV or FCEV (η_{n2}) are adopted from Table 5. The results show that fuel consumption will decrease to 33–34% of that of a conventional ICEV today. The road load reductions in Table 11 and the powertrain technologies assumed in Eq. (2) are comparable to those targeted by the PNGV. Despite the uncertainties, it is reasonable to conclude that it will be possible to reach the goal set by the PNGV without changing the size or performance of the vehicle. The development of new powertrains requires, however, dedicated efforts to improve efficiency in order to attain the potential anticipated in this study.

7. Discussion

This study shows that there is substantial potential for improving the primary energy efficiency for vehicles using alternative powertrains. However, considerable improvements in performance and reductions in cost are necessary to make the alternative powertrains commercially competitive. The common denominator for the alternative powertrains is the electric drivetrain. This paper assumes that a highly developed and efficient electric drivetrain can be attained in the stated time frame, 10–20 years. Most likely, the optimistic efficiencies assumed in this paper will not be attained for a long time. Other performances, such as cost, will be prioritised first in development.

No battery today meets the USABC and PNGV performance targets for BEVs regarding specific energy, specific power, or cost, which are necessary for commercialisation. The BEV is totally dependent on the development of batteries for successful introduction on to the market. With the NiMH battery, an energy efficiency of 81% is possible today, but the potential specific energy for the NiMH battery is too low (80–100 Wh/kg) to be a long-term option to the BEV. The reported potential of 95% efficiency and a specific energy of 150 Wh/kg for lithium–polymer batteries is difficult to validate. According to Kuller [28], at the leading lithium–polymer battery manufacturer (3M/Hydro-Quebec), they have prototype batteries today that meet these targets, see also [19]. The development of lithium–polymer batteries with the stated performance is probably necessary to make the BEV competitive. It has been argued that the lithium–polymer battery suffers from inherently low specific power, and is thus not an alternative for HEVs [18], but recently, lithium–polymer batteries with high specific power have been demonstrated and might be a future alternative to HEVs as well [19].

The technology providing the assumed maximum efficiency of 43% for ICEs exists today. A

---

[4] The PNGV (Partnership of a New Generation of Vehicles) aims at increasing the fuel economy from 27.5 mpg today up to 80 mpg [30].

potential problem facing the HEV with a heat engine is the emissions of NO_X, hydro carbons and particulate matter. A higher compression ratio, and thus higher efficiency, also means a risk of increased emissions of small particles [49]. New engines will have to be characterised by both low emission and high efficiency. The HEV is not dependent on battery development to the same degree as the BEV. HEVs already exist on the market. If the targets for specific power or cost are not be met, it is possible to compromise and sacrifice some of the potential efficiency improvement by allowing the ICE to suffer greater variation in load. This lowers the mean efficiency, but at the same time also the demands on specific power and energy capacity on the battery.

The time perspective for the introduction of FCEVs is longer than for HEVs. Series production of the current FCEV will begin, at the earliest, in 2004 [50], but series production of fully developed fuel cells will probably have to wait until 2010. The fuel cell still requires much development in order to bring costs down to a competitive level and to attain the assumed maximum efficiency of 55% used in our calculations and requires to much platinum in the catalyst in order to reach the long-term goal of a cost of 47 US$/kW set by PNGV [30]. The assumptions in this paper of 55% maximum efficiency and 47% mean efficiency are high, but possible in a 10 year perspective, see, for example [30,38,39,51]. However, 55% maximum efficiency requires that the fuel-cell *system* be optimised. Apart from the fuel cell stack, the system also includes compressors, pumps, etc. [51]. A system based on hydrogen requires a new refuelling infrastructure and complicated fuel storage on board the vehicle. So far, car manufacturers prefer to reform methanol on board the vehicle instead, see conclusions in [40]. This does not require a totally new infrastructure, but lowers the energy efficiency and increases the vehicle weight.

8. Conclusions

This comparative assessment shows that there is potential to double the primary energy efficiency using electric drivetrains in vehicles, such as BEVs, HEVs or FCEVs, compared with present ICEVs. All vehicles with an alternative powertrain have the potential for higher primary energy efficiency than vehicles with an improved conventional powertrain.

BEVs seems to have a small advantage over HEVs and FCEVs from a primary energy efficiency point of view, but given the uncertainties, all alternative powertrains have approximately the same primary energy efficiency when supplied with fossil or biomass fuels. No outright winner amongst the alternative powertrains could be identified from a primary energy efficiency point of view. If the energy carrier is renewable primary electricity, e.g. in a solar photovoltaics future, the BEV will have a higher primary energy efficiency than the FCEV using hydrogen from electrolysis.

Acknowledgements

This work was sponsored by the Swedish Transport and Communications Research Board (KFB). Valuable comments and criticism were made by Dr Bengt Johansson and Professor Lars J. Nilsson, both at the Department of Environmental and Energy Systems Studies at Lund University, and three anonymous reviewers.

References

[1] WEC. Global transport and energy development. The scope of change. London: World Energy Council, 1998.

[2] IEA/OECD. World energy outlook. Paris: IEA/OECD, 1998.

[3] Schipper L, Marie-Lilliu C. Carbon dioxide emissions from IEA countries. Stockholm: KFB, 1999.

[4] IEA-AFIS. Automotive fuels for the future—the search for alternatives. Paris: OECD/IEA, 1999.

[5] Johansson B. Will Swedish biomass be sufficient for future transportation-fuel demands? Energy 1996;21(12):1059–69.

[6] Ecotraffic. The life of fuels. Stockholm, 1992.

[7] Metz N, Sporckmann B. Comparison of the energy consumption and emissions of future drive trains for passenger cars at the year 2000. In: Electric Vehicle Symposium 14, Orlando (FL), 1997.

[8] Wang Q, Deluchi MA. Impacts of electric vehicles on primary energy consumption and petroleum displacement. Energy 1992;17(4):351–66.

[9] OECD/IEA. Electric vehicles: technology, performance and potential. Paris: OECD, 1993.

[10] Wabro R, Wagner U. Energieverbrauchsanalyse von elektro-Pkw-stand der technik und ausblick. ATZ Automobiltechnische Zeitshcrift 1998;100(2).

[11] Amann CH. The stretch for better passenger car fuel economy: a critical look Part 1 and 2. Automotive Engineering International 1998:305–13, 71–6.

[12] Cuddy MR, Wipke KB. Analysis of the fuel economy benefit of drivetrain hybridization. Society of Automotive Engineers 1997;101–9.

[13] Wang M et al. Total energy-cycle energy and emissions impacts of hybrid electric vehicles. In: Electric Vehicle Symposium 14, Orlando (FL), 1997.

[14] Lipman TE, DeLucchi MA. Hydrogen fueled vehicles. International Journal of Vehicle Design 1996;17:562–89.

[15] Reuyl JS, Schuurmans PJ. Policy implications of hybrid-electric vehicles. Final report to NREL, NEVCOR Inc., Stanford (CA), 1996.

[16] DeCicco J, Ross M. An updated assessment of the near-term potential for improving automotive fuel economy. Washington (DC): American Council for an Energy Efficient Economy (ACEEE), 1993.

[17] NRC. Effectiveness of the United States advanced battery consortium as a government–industry partnership. Washington (DC): National Research Council, 1998.

[18] Rand DAJ, Woods R, Dell RM. Batteries for electric vehicles, vol. 1. Exeter: Research Studies Press, 1998.

[19] St-Pierre C et al. Lithium polymer battery for electric vehicle and hybrid vehicle applications. In: Electric Vehicle Symposium 16, Beijing (China), 1999.

[20] Lipman T. The cost of manufacturing electric vehicle batteries. Davis: ITS, University of California, 1999.

[21] Kopf C et al. Development of a multifunctional high power system: meeting the demands of both a generator and traction drive system. In: Electric Vehicle Symposium 14, Orlando (FL), 1997.

[22] Lutz JF, Patel BR. Performance comparison of a 100 kW brush less PM and induction motor system. In: Electric Vehicle Symposium 14, Orlando (FL), 1997.

[23] Sato Y et al. New control methods for high performance PM motor drive system. In: Electric Vehicle Symposium 14, Orlando (FL), 1997.

[24] STOSEB. Framtidens bila—En energi-och miljöstudie. STOSEB: Stockholm, 1994.

[25] BRUSA, 20/4 1999 http://www.rol.ch/BRUSA/fenglish/frame.htm

[26] Corrigan DA et al. Higher power ovonic nickel–metal hydride batteries for electric and hybrid vehicles. In: Electric Vehicle Symposium 14, Orlando (FL), 1997.

[27] Georen P. Personal communication, Department of Applied Electrochemistry, KTH (Sweden), 1999.

[28] Kuller D. Personal communication, 3M/Hydro-Quebec (Canada), 1999.

[29] Sjöblom B, Rehn J, Volvo Aero Corporation Sweden. The Volvo high speed generation hybrid drive and associated combustion system. Energy Conversion & Management 1997;38(1013):1225–35.

[30] NRC. Review of the partnership for a new generation of vehicles, Fourth report. Washington (DC): National Research Council, 1998. p. 122.

[31] Peschka W. The status of handling and storage techniques for liquid hydrogen in motor vehicles. International Journal of Hydrogen Energy 1987;12(11):753–64.

[32] Shelef M, Kukkonen CA. Prospects of hydrogen-fueled vehicles. Progress Energy Combustion Sciences 1994;20:139–48.
[33] James BD et al. Onboard hydrogen storage in fuel cell vehicles. In: Electric Vehicle Symposium 14, Orlando (FL), 1997.
[34] DeLuchi MA, Ogden JM. Solar-hydrogen fuel-cell vehicles. Transportation Research 1993;27A(3):255–75.
[35] Ogden JM et al. Hydrogen energy systems studies. Princeton, NJ: Center for Energy and Environmental Studies, Princeton University, 1995.
[36] Cleghorn SJC et al. PEM fuel cells for transportation and stationary power generation applications. International Journal of Hydrogen Energy 1997;22(12):1137–44.
[37] McNicol BD, Rand DAJ, Williams KR. Direct methanol–air fuel cells for road transportation. Journal of Power Sources 1999;83:15–31.
[38] Kordesh K, Simader G. Fuel cells and their applications. Weinheim: VCH, 1996.
[39] Borroni-Bird CE. Fuel cell commercialisation issues for light-duty vehicle applications. Journal of Power Sources 1996;61:33–48.
[40] Kalhammer FR et al. Status and prospects of fuel cells as automobile engines. Sacramento (CA): State of California Air Resources Board (CARB), 1998.
[41] IPCC. Climate change 1995—impacts, adaptations and mitigation of climate change: scientific-technical analyses. New York: Cambridge University Press, 1996.
[42] Katofsky RE. The production of fluid fuels from biomass. Princeton (NJ): Center for Energy and Environmental Studies, 1993.
[43] Blinge M et al. Livscykelanalys (LCA) av drivmedel Bilagor. Stockholm: KFB, 1997.
[44] Energikomissionen, Omställning av energisystemet. Energikommisionen: Stockholm, 1995.
[45] Gustavsson L. et al., Reducing CO_2-emissions by substituting biomass for fossil fuels. Energy 1995;20:1097–113.
[46] Olsson LO. Fordonskostnadens påverkan vid användande av biodrivmedel. Stockholm: KFB, 1996.
[47] Ogden JM, Nitsch J. Solar hydrogen. In: Johansson TB et al, editor. Renewable energy. Washington (DC): Island Press, 1994.
[48] Lovins AB. Hypercars: the next industrial revolution. In: Electric Vehicle Symposium 13, Osaka (Japan), 1996.
[49] Egnell R. Personal communication, Department of Combustion Engines, LTH (Sweden), 1999.
[50] Daimler–Chrysler. http://www3.daimlerchrysler.com, Date:17/5, 1999.
[51] Johansson K. Personal communication, Department of Chemistry, KTH (Sweden), 1999.
[52] Weiss MA, Heywood JB, Drake EM, Schafer A, AuYeung FF. On the road in 2020—a life-cycle analysis of new automobile technology. Energy Laboratory Report #MIT EL 00-003. Cambridge (MA): MIT, 2000