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# Natural gas as an alternative to crude oil in automotive fuel chains well-to-wheel analysis and transition strategy development

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**Abstract**

Road transport produces significant amounts of $CO_2$ by using crude oil as primary energy source. A reduction of $CO_2$ emissions can be achieved by implementing alternative fuel chains. This article studies $CO_2$ emissions and energy efficiencies by means of a well to wheel analysis of alternative automotive fuel chains, using *natural gas* (NG) as an alternative primary energy source to replace crude oil. The results indicate that NG-based hydrogen applied in fuel cell vehicles (FCVs) lead to largest $CO_2$ emission reductions (up to 40% compared to current practice). However, large implementation barriers for this option are foreseen, both technically and in terms of network change. Two different transition strategies are discussed to gradually make the transition to these preferred fuel chains. Important transition technologies that are the backbone of these routes are traditional engine technology fuelled by compressed NG and a FCV fuelled by gasoline. The first is preferred in terms of carbon emissions. The results furthermore indicate that an innovation in the conventional chain, the diesel hybrid vehicle, is more efficient than many NG-based chains. This option scores well in terms of carbon emissions and implementation barriers and is a very strong option for the future.


*Keywords:* Automotive fuels; Natural gas fuel chains; $CO_2$ emissions; Transition strategies

## 1. Introduction

Large scale use of fossil fuels as primary energy source has resulted in large emissions of $CO_2$, the most important greenhouse gas (GHG). Emissions of GHGs are generally seen as a large problem since a temperature rise caused by the increasing concentrations of GHGs in the atmosphere is likely to influence global climate. Targets for GHG emission reduction are set in the Kyoto Protocol. An important sector regarding GHG emissions is road transport, accounting for nearly 30% of $CO_2$ emissions related to fossil fuel combustion in OECD countries (OECD, 1993). In conventional automotive fuel chains, gasoline and diesel are produced by distillation of crude oil at the refinery. Ninety-nine percent of the energy consumed in road transport is based on the fossil fuel crude oil (IEA/AFIS, 1996). $CO_2$ emissions not only result from automotive fuel combustion on board the vehicle, but also from fuel extraction, transport, production and distribution. In order to accomplish a reduction in $CO_2$ emissions, both the fuel supply industry and the car manufacturing industry are exploring alternative automotive fuels and technologies.

Alternative fuel chains can involve the use of alternative primary energy sources, innovative fuel production methods, new automotive fuels, or innovative vehicle drive trains. Primary energy sources besides crude oil can be natural gas (NG), biomass, coal, and hydro-, wind or solar energy. A wide variety of energy carriers can be derived from these primary energy sources: gasoline, diesel, liquefied petroleum gas (LPG), liquefied natural gas (LNG), compressed natural gas (CNG), methanol, ethanol, hydrogen, and electricity. To produce these energy carriers, different production methods can be employed. For example, diesel can be

*Abbreviations:* CI-Compressed ignition; CNG-Compressed natural gas; FC-Fuel cell; FCV-Fuel cell vehicle; FT-Fisher–Tropsch; GHG-Greenhouse gas; $H_2$-Hydrogen; HEV-Hybrid electric vehicle; ICE-Internal combustion engine; ICEV-Internal combustion engine vehicle; LNG-Liquefied natural gas; LPG-Liquefied petrol gas; NG-Natural gas; SI-Spark ignition

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derived from crude oil by distillation, but also from NG using the Fischer–Tropsch process. Furthermore, fuels can be produced centrally at large-scale plants, locally at retail stations, or somewhere in between. Fuel may also be converted onboard the vehicle. Next to a conventional internal combustion engine (ICE) alternative vehicle power trains can be electric using a battery or fuel cell, or hybrid, using a combination. All these options create a wide range of alternative fuel chains.

The transition to new fuel chains requires large investments and long time frames for adjustments since adaptation of fuel supply, retail stations and vehicles is required. For a solid transition strategy, it is therefore very important to evaluate changes in fuel chains thoroughly. Taking the climate change problem seriously, one may expect that an important evaluation criterion is the carbon emissions associated with future fuel chains. It is only possible to drastically reduce carbon emissions by using either renewable feedstocks or by capturing the carbon from the fossil fuels and storing it outside the atmosphere. The latter is not expected to be a solution for the short-term at a large-scale (Turkenburg and Hendriks, 1999). A key renewable feedstock for automotive fuels is biomass, which can be converted in many different fuel types such as biodiesel, ethanol, and via gasification also methanol, hydrogen and Fisher–Tropsch gasoline. However, biomass availability constraints and relative high costs of total fuel supply chains make a large-scale use of biomass for transport fuel a relatively difficult option for large-scale implementation on the short to medium term. This may change considerably on the long-term[1] (Faaij and Hamelinck, 2002).

It is often stated that we are currently in a transition period towards a sustainable energy system. The best strategy for such a transition period seems to be reducing current GHG emissions and implement changes that are flexible regarding future innovations in the energy sector in order to prevent technological 'lock in' phenomena. A switch from oil based to NG-based fuel chains may be a good way to reduce both the carbon emissions of current fuel chains and to keep a high degree of flexibility regarding future developments for three reasons. First, the carbon emission per unit combustion energy is much smaller for NG. Second, NG can be substituted in time by climate neutral energy carriers like biomass-based synthetic NG or hydrogen. Third, on the short-term NG has a number of other advantages in comparison to crude oil. NG has the advantages of fewer impurities and aromatics than crude oil, which is favorable regarding local pollutants (e.g. $SO_x$, $NO_x$). It is the cleanest and environmentally most acceptable primary fossil fuel regarding its products of combustion (Dicks, 1996). Total recoverable NG resources are more abundant than oil resources and reserves are distributed more evenly world-wide (Amoco, 1999). Various developed countries (the US, Japan, The Netherlands, the UK and Germany) have a NG infrastructure transmitting NG via large pipeline systems. Significant transfer of NG between countries exists (Dicks, 1996). Technological improvements in recovery may further increase production and result in low costs (US Department of Energy, 2000). Low costs and the benefit of existing infrastructure make NG favorable to other alternatives on the short term. It comprises available options, possibly temporary, before complete $CO_2$-free fuel chains can be attained. Proven reserves, established infrastructure and trade, make NG the most available alternative primary fuel on a short term (Dicks, 1996) in terms of supply.

[1] We define short term as $<10$ years, medium term as 10–20 years and long term as $>20$ years.

NG in automobiles is not used at a large scale. However, NG can be used directly as an automotive fuel either liquefied (LNG) or compressed (CNG). It can also serve as a primary energy source for hydrogen, methanol or Fischer–Tropsch (FT) diesel production. These automotive fuels from NG and their application in an internal combustion engine vehicle (ICEV) or fuel cell vehicle (FCV) are considered in this article (see Fig. 1). The possibility of using NG during a transition period and the variety of fuel chains arising from this option leads to the following question, addressed in this article:

*What is the potential $CO_2$ emission reduction per vehicle kilometre on the short term when conventional oil-based fuel chains are substituted by alternative fuel chains using NG as primary energy source?*

The NG fuel chain options differ considerably in terms of technical and infrastructural changes that are required. An evaluation of potential chains on just $CO_2$ emissions is therefore not enough. In the development of a transition strategy it is important to make a trade off between GHG emission reduction, costs and implementation barriers that are to be expected. As further explained in Section 3, future fuel costs are surrounded by huge uncertainties for several reasons like strongly fluctuation feedstock prices and the fact that many options overlap in terms of cost ranges. Furthermore, the energy costs (before taxes) are not dominant for the car owner. For these reasons we do not focus on a cost assessment in this article. We expect that the expected implementation barriers are more important in the evaluation of new fuel chains. In the second part of this article we therefore focus on answering the following question:

*What are potentially successful transition strategies taking the implementation barriers and carbon emissions associated with these alternative fuel chains into account?*

This is not the first study that considers carbon emissions from alternative fuel chains. We use a well-to-wheel method for the analysis. This method has been used in other studies too (Stodolsky et al., 1999; Gover, 1996; Wang, 1999; Johansson et al., 1992; IEA/AFIS, 1996, 1999; Williams et al., 1995; Faaij et al., 2000). Most studies, however, study long-term options to reduce $CO_2$ emissions from automotive fuel chains. Faaij et al. (2000) studies biomass-based fuel chains, considering a time frame of about 20–30 years. Johansson et al. (1992) and the IEA (1996, 1999) study a variety of fuel chains including hydrogen production by electrolysis, but they do not study NG-based fuel chains. NG is included as a substitute for crude oil in automotive fuel chains in a number of studies (Stodolsky et al., 1999; Gover, 1996; Wang, 1999; Williams et al., 1995). Gover (1996) and Williams et al. (1995) only study a small number of NG-based chains. The focus of Gover (1996) is specifically on future fuel chain options for the UK and Williams et al. (1995) focus mostly on biomass as primary energy source. Data in (Williams et al., 1995) on hydrogen and methanol production from NG is reviewed and used in our analysis. Stodolsky et al. (1999) study efficiencies of a larger number of NG fuel chain options, as is the case in this article, and also estimates $CO_2$ emissions. We distinguish from this study by using data ranges and a more detailed approach to calculate $CO_2$ emissions. Wang (1999) also uses such a detailed approach to determine $CO_2$ emissions but the study has a much broader scope for situations in the US Finally, we distinguish from all of these studies by integrating information about implementation barriers and carbon emissions in the development of transition strategies for alternative fuel chains.

## 2. Method

Fuel chains are compared using a so-called Well-to-Wheel approach. In this approach all life cycle steps of the fuel chains (see Fig. 2) are analysed in terms of energy use and related carbon emissions. In fact, the approach is a comparative life cycle assessment of fuel chains but only focusing at energy requirements and carbon emissions. The name well-to-wheel stems from the fact that carbon emissions are taken into account that originate from a crude oil or gas *well* till the combustion emissions from a vehicle to produce *wheel* power.

Step 1 of the method is to determine all the life cycle steps of the fuel chains studied. Fig. 2 states these life cycle steps for the reference fuel chain.

Step 2 is to determine for every life cycle step the energy requirements, energy efficiency and carbon emissions. Since different sources state different numbers regarding energy requirement, we use data ranges: best case, probable case and worst case data. The best case represents an optimistic view with modern facilities and advanced technologies. The probable case represents the energy requirement most likely realized in practice. Here, energy requirements that are rather optimistic, but regarded achievable with modern technologies, are considered. The worst case is set by high-end of the energy requirement data range found in literature. By using ranges, conclusions influenced by differences in fuel chain characteristics, or by comparing data of older plants with optimal and up-to-date situations, are avoided.

To determine the energy use per life cycle step we did a literature review and compared these data with data from Shell (Royal Dutch Shell Group, 1998a, b; Shell International Exploration & Production, 1997; Shell International Oil Products, 1998; Assink et al., 2000).

The energy requirement and carbon emissions per life cycle step are based on the energy efficiency per life cycle step. This is determined according to Formula 1 based

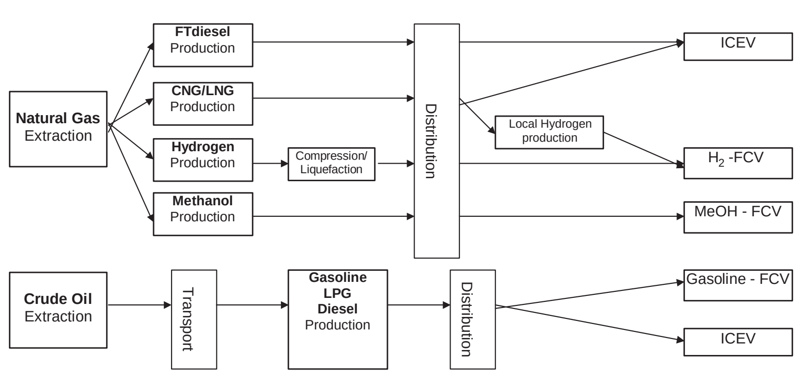


Fig. 1. Fuel chains considered in this paper.

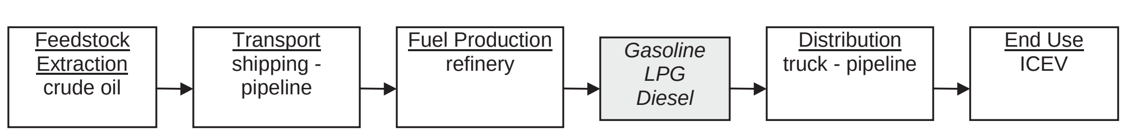


Fig. 2. Well-to-Wheel, reference fuel chain.

on lower heating values:

$$\text{Efficiency}(\%) = \text{energy output (GJ)}/ \times \text{energy input (GJ)} \times 100\%. \quad (1)$$

Determining the energy requirement per life cycle step results directly from combining the energy efficiency of that step and the energy output. All energy use is translated into primary energy use using efficiencies of electricity and heat production of 45% and 90%, respectively. The $CO_2$ emissions are determined by using the carbon emission factors of the energy sources. Table 5 shows carbon intensities of process fuels and electricity. For the probable case a process fuel mix is used based on Shell (Royal Dutch Shell Group, 1998a, b; Shell International Exploration & Production, 1997; Shell International Oil Products, 1998; Assink et al., 2000) and Wang (1999) data. When different fuel types are mentioned for the same process we allocated the $CO_2$ intensive fuels to the worst case, and the $CO_2$ extensive fuels to the best case. Energy consumed by production or generation of process fuels is included in calculating fuel chain efficiencies.

The energy efficiency of the final life cycle stage, end use of the automotive fuel by the vehicle, is most difficult to determine. For the FCV we did a literature review to determine the efficiencies of the most important components used to build a FCV. Based on these we calculated the total vehicles efficiency and compared this with other sources. For the ICEV we use efficiency ranges based on literature research (CBS, 1998; Baert, 2000; Oak Ridge National Laboratory, 1998; BOVAG, 2000; Partnership for New Generation Vehicles, 1999; Quissek, 1997; Ogden et al., 1999; Carpetis and Nitsch, 1999; Ekdunge and Råberg, 1998; Specht et al., 1998; Höhlein et al., 1999; Borroni-Bird, 1996; Hart and Hörmandinger, 1998; Jamal and Wyszynski, 1994; Dönitz, 1998; Barbir and Gomez, 1997; Klaiber, 1996; Thomas et al., 2000).

The final step (step 3) of our method is determining total fuel chain efficiency. This is defined as the ratio of wheel power needed by the vehicle and total energy input in the fuel chain. $CO_2$ emissions and energy consumption are eventually presented per kilometer by using vehicle fuel economy.

## 3. Results

### 3.1. Reference chains: the supply of crude oil derived fuels

Fuel supply in the reference case is very efficient, since automotive fuels are provided and used this way for a long time. Efficiencies are optimized, although some further improvements may still be possible. The reference fuel chain starts with crude oil extraction. The crude is transported to refineries, where gasoline, diesel and LPG are produced. Distribution to retail stations and combustion in the ICEV form the last fuel chain stages. Table 1 presents the results for crude oil chains and the exact ratios of the process fuel mix are stated in the footnotes.

The results as presented in Table 1 are based on the following data and assumptions. Crude oil is extracted with an efficiency of about 95–97% (Royal Dutch Shell Group, 1998a; Shell International Exploration & Production, 1997; Gover, 1996; Wang, 1999; Johansson et al., 1992; Specht et al., 1998; Höhlein et al., 1999). Primary treatment separates light gases and water from the crude oil before transport. The exact amount of energy consumption depends on the effort and recovery methods necessary. Ninety-six percent is used for the probable case. To consider the case of a high-pressure field, 99% (Wang, 1999; Specht et al., 1998) is regarded the upper limit. In the worst case efficiency is 94% (Gover, 1996; Shell International Exploration & Production, 1997), which is plausible in case enhanced recovery methods are applied, before oil recovery from the field will become too costly. $CO_2$ emissions result from combusting process fuels and flaring (see Table 5 for the assumed carbon emission due to the use of process fuels). Here, it is assumed that mainly associated gases and crude oil are used as process fuels, besides the use of small amounts of diesel, gasoline, electricity and residual fuel. After extraction, the crude is transported by sea tanker and pipelines to refineries located in consuming areas. Transport only requires a very small amount of energy relative to the energy contained by the crude oil. An efficiency of 99% (Wang, 1999; Johansson et al., 1992; IEA/AFIS, 1996; Shell International Oil Products, 1998; Specht et al., 1998) is used with a deviation of 0.5% for the worst and best case. Within the refinery, crude oil is converted into various products by distillation. Product yields vary between and within refineries. Higher yields because of further upgrading results in higher energy consumption. Besides the amount of automotive fuel produced, more demanding fuel specifications increase a refinery's energy requirement. Extra energy consumption by refineries did not occur these last years because of energy savings (Shell International Oil Products, 1998). This may no longer be possible when regulations become more stringent. Today, the overall refinery efficiency, regarding the energy content of total crude oil input and product output, is 94% (Royal Dutch Shell Group, 1998a; CBS, 1998). Total energy consumption and accompanying $CO_2$ emissions are allocated among all products to determine how much is related to gasoline and diesel production. Roughly two-thirds of crude input ends up within automotive fuel ranges. A large share of the remaining will results in heavy fuel oils (Royal Dutch Shell Group, 1998b). The latter does not require much processing and production at 98% efficiency is assumed.

Using this information, and given the fact that diesel requires less processing than gasoline and LPG, efficiency of gasoline, diesel and LPG production are estimated to be 88%, 95%, and 92%, respectively.[2] Other studies quote efficiency for gasoline production between 82% and 92%. For diesel, efficiency data is between 89% and 96%, although most estimates are about 95% (Wang, 1999; Johansson et al., 1992; IEA/AFIS, 1996, 1999; Williams et al., 1995; Specht et al., 1998; Höhlein et al., 1999; Borroni-Bird, 1996). It is assumed here that the refinery is self-supporting, implying that crude oil is the only external energy input. $CO_2$ emissions result from combusting heavy fuel oil and residues, still gas, and NG or generating electricity. Using these efficiency estimates, $CO_2$ emissions are attributed to diesel, gasoline and LPG production. The final stage of fuel supply is distribution of automotive fuels, requiring less energy than crude transport since refineries are situated in consuming areas. Efficiency is over 99% (Wang, 1999; IEA/AFIS, 1999; Williams et al., 1995; Borroni-Bird, 1996). Most of the energy input is diesel, needed by trucks. Small amounts of energy are provided by electricity for pipelines or heavy fuel for sea transport.

### 3.2. Supply of NG-based fuels

Table 2 presents the main outcomes for the supply of NG-based fuels.

The data are based on the following input data and assumptions.

Extraction of NG is very efficient and depends on field pressure and gas quality. When impurities are low, and field pressure is high, energy demand can be negligibly small (Johansson et al., 1992). More difficult extraction sites can result in an energy consumption up to 5% of the energy content of the extracted gas, including flaring and losses (Stodolsky et al., 1999; Wang, 1999; Johansson et al., 1992; IEA/AFIS, 1999). For both extraction and processing, efficiency varies between 95% and 100%. Feedstock transport is not regarded, since automotive fuel production can take place at the wellhead site. NG may contain carbon dioxide in concentrations ranging from very low to sometimes significantly more than 10%. In the present study we will assume that the $CO_2$ concentration in NG is small and can be ignored.

#### 3.2.1. CNG and LNG

CNG and LNG production require electricity. The exact energy input depends on intake pressure. Efficiency of CNG production is around 96% (Wang, 1999; Johansson et al., 1992), yet higher efficiencies of 98–99% (Wang, 1999; Höhlein et al., 1999) are quoted as well. Since process energy is mainly provided as electrical power for electric compressors, efficiency considering primary energy use is lower, specifically 93% in the probable case. Apart from carbon dioxide NG may contain small quantities of nitrogen, oxygen, sulfur compounds, and water. Compounds that would freeze during liquefaction have to be removed. LNG production requires a series of refrigeration steps, efficiency is 90% (Wang, 1999; Johansson et al., 1992; IEA/AFIS, 1999). Potential GHG emissions from refrigerants are not taken into account.

When intake pressure is high, and CNG is transported by pipelines, efficiency of CNG distribution may be 99% (Wang, 1999), 96–97% (OECD, 1993; Wang, 1999) is used for the probable case. Distribution of LNG requires more energy. LNG is transported in storage tanks by trucks or sea tanker. Storage, shipment and regasification of LNG requires about 2–9%, while 1–2% of gas may be lost by boil off (Johansson et al., 1992). Therefore, efficiency for LNG distribution ranges from 91% to 97% (94% in the probable case).

#### 3.2.2. Hydrogen

Hydrogen is assumed to be produced by steam reforming NG.[3] This process can take place centrally at a large-scale plant. To avoid problems associated with hydrogen distribution, reforming could take place locally at retail stations after distribution of CNG. For small steam reformers, efficiency would be lower, since heat integration and production of useful steam by waste heat on a small scale is more difficult. Therefore, two ranges of efficiency, one for central production and one for local production, are considered. For locally produced hydrogen an efficiency range of 65–73% (Wang, 1999; Klaiber, 1996; Thomas et al., 2000) is used here, while 73–78% (Stodolsky et al., 1999; Wang, 1999; Williams et al., 1995; Borroni-Bird, 1996) is used for production at a large-scale central facility. After production, hydrogen has to be compressed or liquefied to be distributed. Liquefaction requires 40–50 $MJ_e$ of

[2] LPG is also a by-product in crude oil and natural gas production (associated gas). Worldwide about 40% of the LPG is produced in crude oil refining and 60% is produced during crude oil and natural gas extraction. The analysis in this article is based on LPG produced during oil refining. For LPG produced during natural gas and crude oil extraction (associated gas), the estimates for efficiencies and $CO_2$ emissions would of course be slightly different. Transporting LPG from the extraction site to the consumer will be more inefficient compared to crude oil transport (compare the transport of LNG in Table 2 having an efficiency of 89–97%). On the other hand, the LPG does not have to be produced anymore. The estimates for LPG produced during natural gas and crude oil extraction can therefore be expected to be in the range presented here for LPG produced in oil refineries.

[3] Hydrogen can also be produced through gasification of heavy oil fractions or coal. These processes, which are not considered here, have significantly higher $CO_2$ emissions than steam reforming of natural gas.

Table 1
Supply of gasoline, diesel and LPG

| Crude oil[a] | Efficiency (%)[b] including energy consumption by producing process fuels | | | $CO_2$ kg/GJ incl. $CO_2$ emissions from the production of process fuels | | |
|---|---|---|---|---|---|---|
| Case | Worst | Probable | Best | Worst | Probable | Best |
| Extraction[c] | 92.3 | 95.0 | 98.8 | 5.9 | 3.6 | 0.8 |
| Transport[d] | 98.2 | 98.9 | 99.4 | 1.3 | 0.9 | 0.4 |
| *Fuel production*[e] | | | | | | |
| Gasoline | 81.5 | 88.0 | 91.5 | 16.0 | 9.4 | 6.3 |
| Diesel | 89.0 | 95.0 | 96.0 | 9.7 | 3.6 | 2.8 |
| LPG | 90.0 | 92.0 | 97.0 | 7.8 | 6.0 | 2.1 |
| *Distribution* | | | | | | |
| Gasoline[f] | 98.1 | 99.0 | 99.9 | 1.4 | 0.7 | 0.1 |
| Diesel[b] | 98.1 | 99.0 | 99.9 | 1.4 | 0.7 | 0.1 |
| LPG[g] | 96.3 | 97.6 | 99.4 | 2.7 | 1.8 | 0.4 |
| *Total supply*[h] | | | | | | |
| Gasoline | 73 | 82 | 90 | 26 | 15 | 8 |
| Diesel | 80 | 88 | 94 | 18 | 9 | 4 |
| LPG | 79 | 85 | 95 | 19 | 13 | 4 |

[a] Process efficiency and input fuels: see data from Shell (1999) (see also Royal Dutch Shell Group, 1998a, Shell International Exploration & Production, 1997, Shell International Oil Products, 1998), Wang (1999), IEA/AFIS (1999) (see also IEA/AFIS, 1996), Gover (1996), Johansson et al. (1992), Specht et al. (1998) (see also Carpetis and Nitsch, 1999), Höhlein et al. (1999) (see also Ekdunge and Råberg, 1998), and Borroni-Bird (1996) (see also Specht et al., 1998).

[b] Here concerns efficiencies where energy consumption from production of process fuels, such as electricity is taken into account. Efficiencies of producing process fuels are presented in Table 4.

[c] Emissions with respect to a GJ of crude oil. Process efficiency: worst 94%, probable 96%, best 99%. $CO_2$ emissions are calculated assuming a process fuel mix consisting of residual fuel, diesel, electricity, gasoline, crude and associated gas, respectively, in the following ratios in the worst case 1%, 15%, 20%, 4%, 60%, 0%; in the probable case 1%, 15%, 18%, 4%, 31%, 31%; in the best case 1%, 15%, 16%, 4%, 0%, 64%. $CO_2$ emissions for combustion of process fuels are shown in Table 4.

[d] Emissions with respect to a GJ of crude oil. Process efficiency: worst 98.5%, probable 99%, best 99.5%. Energy provided by heavy fuel oil with a small contribution of diesel and electricity, respectively, in fuel mix ratios: worst case 93%, 0%, 7%; probable case 92%, 2%, 6%; best case 92%, 4%, 4%.

[e] Emissions with respect to a GJ of automotive fuel. Here, it is assumed that all process fuels are produced within the refinery, therefore process efficiency is equal to efficiency including process fuel production. Consumption of residual fuel, heavy fuel, still gas, electricity and natural gas in fuel mix ratios: worst case 25%, 15%, 40%, 18%, 2%; probable case 20%, 10%, 45%, 15%, 10%; best case 18%, 8%, 52%, 12%, 10%, respectively.

[f] Emissions with respect to a GJ of automotive fuel. Process efficiency: worst 98.5%, probable 99.2%, best 99.9%. Consumption of diesel, heavy fuel and electricity in fuel mix ratios: worst case 66%, 22%, 12%; probable case 70%, 20%, 10%; best case 74%, 18%, 8%, respectively.

[g] Process efficiency: worst 97%, probable 98%, best 99.5%. Fuel mix identical to gasoline and diesel case. Energy costs for distributing LPG are higher, because of a lower calorific value per litre and pressurised transport.

[h] Emissions with respect to a GJ of automotive fuel. To produce 1 GJ of gasoline, 1.23 GJ (worst), 1.14 GJ (probable) and 1.09 GJ (best) crude oil has to be extracted. To produce 1 GJ diesel, 1.12 GJ (worst), 1.05 GJ (probable) and 1.04 GJ (best) crude oil has to be extracted. To produce 1 GJ LPG, 1.11 GJ (worst), 1.09 GJ (probable) and 1.03 GJ (best) crude oil has to be extracted. $CO_2$ emissions for extraction and transport are multiplied by the amount of crude oil necessary in each case.

electricity per kg of hydrogen (Johansson et al., 1992; Carpetis and Nitsch, 1999; Klaiber, 1996), resulting in an efficiency of 55–67% on a LHV basis. Distributing liquid hydrogen requires cooling and compression. Isolation and recovery systems may be used to avoid leakage and boil off losses. Sea transport and trucks can distribute the hydrogen contained by tanks. Energy consumption by transport, cooling and compression depends on the distance traveled. An efficiency of 94% for sea transport, 84% including hydrogen losses, is estimated by Johansson et al. (1992). Wang (1999) uses a high estimate of 95% for distributing liquid hydrogen. Here, it is estimated that fuel consumption by transportation, leading to $CO_2$ emissions, results in an efficiency of 93–95%. Hydrogen losses of 5–15% are taken into account, leading to efficiencies between 78% and 90%. Compression of hydrogen is less energy intensive. It requires about 7–14 $MJ_e$ of electricity to compress a kg of hydrogen to a pressure of 350 bar, equivalent to an energy efficiency of 88–94%. Distribution via pipelines results in electricity usage by compressors. Again, next to intake pressure, the amount of necessary electricity depends on the distance between the hydrogen production site and the retail site. An efficiency range from

Table 2
Supply of CNG, LNG, hydrogen, methanol, FTdiesel

| Natural gas[a] | Efficiency (%) including energy consumption by producing process fuels | | | $CO_2$ kg/GJ incl. $CO_2$ emissions from the production of process fuels | | |
|---|---|---|---|---|---|---|
| Case | Worst | Probable | Best | Worst | Probable | Best |
| Extraction[b] | 94.3 | 96.9 | 100.0 | 6.0 | 2.9 | 0.0 |
| *Fuel production* | | | | | | |
| CNG[c] | 88.1 | 92.8 | 88.2 | 8.0 | 4.7 | 1.2 |
| LNG[d] | 87.6 | 89.2 | 90.6 | 8.6 | 7.3 | 6.3 |
| $H_2$ local production[e] | 62.0 | 67.5 | 71.3 | 95.9 | 88.0 | 83.4 |
| $H_2$ production[f] | 69.6 | 72.3 | 76.1 | 85.3 | 82.1 | 78.0 |
| *Liquefaction $H_2$*[g] | *35.4* | *47.8* | *67.2* | *118.0* | *65.0* | *29.0* |
| *Compression $H_2$*[h] | *76.7* | *83.8* | *87.6* | *18.0* | *11.5* | *8.4* |
| Methanol[i] | 47.2 | 68.3 | 70.1 | 56.6 | 17.9 | 15.6 |
| FTdiesel[j] | 54.0 | 65.0 | 70.0 | 30.8 | 18.3 | 15.3 |
| *Distribution* | | | | | | |
| CNG[k] | 93.3 | 96.6 | 99.2 | 4.3 | 2.2 | 0.5 |
| LNG[l] | 87.6 | 92.6 | 96.4 | 9.8 | 5.6 | 2.6 |
| Compressed $H_2$[m] | 80.2 | 85.7 | 93.6 | 14.7 | 9.9 | 4.1 |
| Liquid $H_2$[n] | 77.8 | 82.8 | 89.6 | 7.8 | 6.1 | 4.6 |
| Methanol[o] | 95.0 | 96.3 | 97.6 | 3.7 | 2.7 | 1.7 |
| FTdiesel[p] | 96.4 | 97.8 | 99.3 | 2.6 | 1.6 | 0.5 |
| *Total fuel supply* | | | | | | |
| CNG | 79 | 87 | 97 | 18 | 10 | 2 |
| LNG | 74 | 81 | 88 | 24 | 16 | 9 |
| Compressed $H_2$[q] | 48 | 56 | 66 | 126 | 107 | 91 |
| Liquid $H_2$[e] | 25 | 34 | 51 | 236 | 170 | 114 |
| Comp. $H_2$ local production[r] | 43 | 53 | 63 | 141 | 113 | 94 |
| Methanol[s] | 44 | 65 | 69 | 72 | 25 | 17 |
| FTdiesel[t] | 50 | 62 | 70 | 45 | 24 | 16 |

[a] Process efficiency and input fuels: see data from Wang (1999), Johansson et al. (1992), IEA/AFIS (1999) (see also IEA/AFIS, 1996), and Stodolsky et al. (1999). $CO_2$ emissions by combustion of process fuels are shown in Table 4.

[b] Includes extraction and processing to remove impurities. $CO_2$ emissions are calculated with respect to a GJ of NG.

- NG extraction: Process efficiency: 97–99–100%. Fuel mix residual fuel, diesel, electricity, gasoline, feed loss ($CH_4$) and natural gas, respectively, in fuel mix ratios: worst case 1%, 9.5%, 1.5%, 1%, 12%, 75%; probable case 1%, 10%, 1%, 1%, 10%, 77%; best case 1%, 10%, 0.5%, 1%, 0%, 87.5%.
- NG processing: Process efficiency: 97.5–98.0–100.0%. Fuel mix diesel, electricity, feed loss ($CH_4$) and natural gas, respectively, in fuel mix ratios: worst case 1%, 4%, 7%, 88%; probable 1%, 3%, 6%, 90%; best case 1%, 2%, 5%, 92%.
- *$CH_4$ loss*: Global warming potential calculated by using its $CO_2$ equivalent (multiplied by factor 21).

[c] Process efficiency: 94–96–98.8%. Process fuels: electricity, NG in ratios 90:10, 70:30, 50:50.

[d] Process efficiency: 89–90–91%. Process fuels: electricity, NG in ratios 10:90, 5:95, 2:98.

[e] See central production (pl. see footnote f).

[f] Process efficiency: 73–75–78%. Process fuels: NG, electricity in ratios 96:4, 97:3, 98:2. NG carbon input released as $CO_2$.

[g] Process efficiency: 55–67–82%. Process fuels: Electricity (100%). Especially the efficiency of liquefaction decreases because the efficiency of producing process fuels (here electricity generation) is taken into account.

[h] Process efficiency: 88–92–94%. Process fuels: electricity (100%).

[i] NG only input fuel. Part of the NG input is used as process fuel causing $CO_2$ emissions. Part of the carbon of the NG input is contained by a GJ of produced MeOH (18.82 kg carbon/GJ MeOH) not resulting in $CO_2$ emissions in this stage.

[j] Process efficiency: 54–65–70%. Natural gas input. The amount of $CO_2$ produced depends on carbon content of the output. Carbon efficiencies of 72%, 80% and 82% used for the worst, probable and best case, respectively (see Shell, 2000 (see also Quissek, 1997; Henderson and Clark, 1990), Wang, 1999; USDOE/ANL, 1999 (see also Mallant, 1999)).

[k] Process efficiency: 96.3–98.0–99.5%. Process fuels: electricity, NG in ratios 70:30, 60:40, 50:50.

[l] Pressure: 350 bar. Process efficiency: 90–93–97%. Process fuel: electricity 100%.

[m] Process efficiency: 91–94–97%. Process fuels: electricity, heavy fuel, diesel, NG in ratios 30:50:20:0, 15:50:20:15, 10:50:20:20.

[n] Process efficiency of transportation: 93–94–95%. Liquid hydrogen transport by sea tanker, truck or pipelines for short distances. Process fuel mix: heavy fuel oil, diesel, electricity in ratios 30:60:10, 25:70:5, 20:78:2. Hydrogen losses 5–15%, resulting in a decrease of process efficiency by a factor 0.85, 0.89 (Johansson, 1992), or 0.95, in the worst, probable and best case, respectively.

[o] Process efficiency: 96–97–98%. Process fuels and ratios: see gasoline.

[p] Efficiency is calculated by multiplying process efficiencies of crude oil transport *and* distribution of oil-derived diesel, since refining takes place in consuming areas, here it is assumed FTdiesel is produced at the wellhead site. Process fuels and ratios: see diesel.

[q] 1.32 GJ (worst), 1.29 GJ (probable), 1.26 GJ (best) of NG is extracted to produce 1 GJ central produced hydrogen.

[r] Before local production of $H_2$, CNG is distributed. Efficiency is determined by efficiencies of NG extraction, CNG production, CNG distribution, $H_2$ production at the retail station and compression. 1.55 GJ (worst), 1.45 GJ (probable), 1.32 GJ (best) of NG is extracted to produce and deliver 1 GJ of liquid hydrogen.

[s] 1.98 GJ (worst), 1.40 GJ (probable), 1.39 GJ (best) of NG is extracted to produce 1 GJ of methanol.

[t] 1.85 GJ (worst), 1.54 GJ (probable), 1.43 GJ (best) of NG is extracted to produce 1 GJ of FTdiesel.

90% (Stodolsky et al., 1999) to 97% (Wang, 1999) is considered, assuming less hydrogen losses than in the case of liquid hydrogen distribution. When hydrogen is produced at the retail station, CNG distribution has taken place. Compression of $H_2$ before refueling is still necessary. Other hydrogen storage technologies such as metal hydrides are not included in this study.

### 3.2.3. Methanol

Methanol can be synthesized from NG after producing synthesis gas by steam methane reforming (SMR). While older plants may have efficiencies of 50–60% (Johansson et al., 1992; IEA/AFIS, 1999), a typical number for methanol plants today is 68% (Wang, 1999). A modern methanol plant can reach an efficiency of 70% (Johansson et al., 1992). Excess steam produced can be exported. Considering these efficiencies, and NG as only input fuel, 1.4–2.0 GJ of NG has to be extracted to produce a GJ of methanol. For methanol distribution, efficiency is similar to gasoline, although a lower energy content per litre (15.6 vs. 31.2 MJ/l) increases energy consumption to some extent.

### 3.2.4. Fischer–Tropsch diesel

Fischer–Tropsch diesel (FTdiesel) from NG is considered here. This fuel chain combines advantages of diesel (high end use efficiency) with advantages of NG as a feedstock. FTdiesel is synthesized after synthesis gas production by partial oxidation and steam reforming of NG. Synthesis gas with the appropriate $CO/H_2$ ratio is used to produce middle distillates by heavy paraffin synthesis, the Fischer–Tropsch process. Products are upgraded by hydrocracking, implying a little extra hydrogen is needed as input fuel. Process efficiency depends on efficiency of synthesis gas production, on the amount of NG input that can be converted into $C_5+$ and on heat recovered from the exothermic reaction. For paraffin synthesis the maximum efficiency is about 78% on a LHV basis. Autothermal reforming for synthesis gas production has to have an efficiency of 89% to establish an overall efficiency of 70%. This is considered to be a high estimate. For the probable case an overall efficiency of 65% (Stodolsky et al., 1999) is used. Carbon efficiency determines the amount of $CO_2$ emitted by FTdiesel production. A carbon efficiency of 72–82% is used. It is mentioned that the Fischer–Tropsch process might also export steam or power. In this case, which is not further discussed here, the emission of $CO_2$ expressed in kg per GJ of Fischer–Tropsch product is obviously reduced. Distribution of FTdiesel is equal to distribution of oil-derived diesel, except for the fact that transport from the NG wellhead site, where fuel production takes place, to consuming areas occurs in this final stage before distribution to retail stations.

Table 3
Energy efficiencies of components of FCV and overall efficiencies

| | Gasoline FCV (%) | Hydrogen FCV (%) | Methanol FCV (%) |
|---|---|---|---|
| Fuel processor | 78 | | 75–85 |
| Fuel stack | 52–54 | 58–62 | 53–55 |
| Loss due to auxiliaries | −20 | −10 | −10 |
| Electric drive train | 75–84 | 75–84 | 75–84 |
| Overall efficiency | 17–24 | 35–42 | 23–29 |

## 3.3. Fuel utilisation by vehicles

Eventually, all automotive fuels can be combusted by ICEs to provide wheel power for a passenger car. A fuel cell generating electricity for an electric drive is an alternative currently being developed. Table 3 states the energy efficiencies as used in the calculation, below these numbers are explained.

### 3.3.1. ICEVs

In the reference chain, gasoline is combusted in a spark ignition (SI) ICE, diesel in a compression ignition (CI) ICE. The latter is more efficient, since the engine's compression ratio is higher. Since a vehicle weight of 1150 kg is regarded about average in The Netherlands (Baert, 2000), a Volkswagen Golf (1130 kg, BOVAG, 2000) is assumed to represent efficiencies. The Extra Urban Driving Cycle results in efficiencies of 20% and 25% for the gasoline and diesel version, respectively (CBS, 1998; Baert, 2000; Oak Ridge National Laboratory, 1998; BOVAG, 2000; Partnership for New Generation Vehicles, 1999; Quissek, 1997; Oak Ridge National Laboratory, 1998). An SI engine running on a gaseous fuel (LPG, CNG, LNG or $H_2$) has an efficiency that is slightly higher than in the gasoline case, due to a higher compression ratio. Most vehicles using gaseous fuels have bi-fuel engines and do not optimally use this advantage. For gaseous fuels considered, an improvement of 1% with respect to the gasoline engine is used.

In hybrid vehicles energy from braking is recovered and stored by a battery. In a parallel hybrid, the battery weight is kept low, since it is only used to store the energy recovered. According to Stodolsky et al. (1999) regenerative braking saves approximately 10%, while another 15% may be saved during idling and deceleration. The hybrid vehicle case is modeled here for the most efficient ICE vehicle, the diesel vehicle. Based on (Stodolsky et al., 1999) probable vehicle efficiency is determined to be 28%.

### 3.3.2. FCVs

The calculated efficiencies of three FC vehicles are stated in Table 3: gasoline FCV, hydrogen FCV and methanol FCV. The calculated efficiencies are based on efficiencies of the components of the FCV. Below, the data input for Table 3 is discussed.

The gasoline FCV contains a fuel processor to convert gasoline in a hydrogen rich synthesis gas ($H_2$ content 38%, Ogden et al., 1999) by partial oxidation at an efficiency of 78% (Assink et al., 2000). Since the feed is diluted, the fuel cell uses about 80–82% of the hydrogen input (Appleby, 1993). The fuel cell stack operates at an efficiency of 52–54% (Assink et al., 2000) when gasoline reformat is used. Auxiliaries cause extra energy losses of about 20% (Hart and Hörmandinger, 1998). The efficiency of the electric drive is between 75% (Höhlein et al., 1999) and 84% (Heck and Schüers, 1999). Using an electric drive operating at 80% (Stodolsky et al., 1999; Ekdunge and Råberg, 1998), the efficiency of the gasoline FCV in the probable case is 21%. The best and worst cases result in efficiencies of 24% and 17%, respectively.

Direct re-fuelling of hydrogen makes the FCV less complex, and more efficient, although hydrogen storage without high-energy losses (due to additional weight or boil-off) is still a problem to overcome. The efficiency of the fuel cell stack can reach 60% (Mallant, 1999) when pure hydrogen is the input fuel. A lower limit of 58%, and an upper limit of 62% are used here (Stodolsky et al., 1999; Hart and Hörmandinger, 1998). Again, efficiency of the electric drive is between 75% and 84%. Since the input gas is not diluted, hydrogen utilization is high, and auxiliaries consume less than in case of gasoline-reformat. When 90% of the hydrogen can be used by the fuel cell to generate electricity, and auxiliaries are assumed to consume 10% of total energy input, the efficiency of the FCV is about 35–42%.

Methanol can also be used as a fuel. The synthesis gas produced by steam reforming of methanol onboard the FCV has a much larger hydrogen content (75%) than by partial oxidation of gasoline. Therefore, hydrogen utilization is higher, the fuel cell stack's efficiency is higher, and energy losses by compression are less. An efficiency range of 75–85% (Ogden et al., 1999; Hart and Hörmandinger, 1998; Thomas et al., 2000; Mallant, 1999) for synthesis gas production (LHV basis) is used. Efficiency of the fuel cell stack is somewhere between the efficiency using pure hydrogen and using gasoline, and is estimated to be 53–55% (Stodolsky et al., 1999; Assink et al., 2000; Dönitz, 1998). A hydrogen utilization of 84% and auxiliary losses of 10% lead to a FCV efficiency of 23–29%.

We compare these efficiency ranges with data from literature. Ogden et al. (1999) simulated fuel consumption for a FCV including a battery, fuelled by hydrogen, methanol or gasoline, on a driving cycle. The direct hydrogen FCV used 0.7 MJ/km, while the methanol and gasoline consumed 1.1 MJ/km (3.4 l/100 km) and 1.0 MJ/km (3.3 l/100 km) on a combined driving cycle. Considering the wheel power needed by the vehicles described, efficiencies are about 40%, 28% and 30%, respectively. Several facts in these results are noticeable in comparison to the ranges stated above. First, for hydrogen and methanol efficiencies are within ranges mentioned, in contrast to the gasoline FCV. In Ogden et al. (1999) gasoline shows a slightly better efficiency than the methanol FCV, although the hydrogen content of the synthesis gas is much lower in this case. Most studies (Ekdunge and Råberg, 1998; Höhlein et al., 1999; Dönitz, 1998; Klaiber, 1996; Thomas et al., 2000) estimate efficiency for a pure hydrogen FCV will be between 30% and 40%, using 0.9–1.4 MJ/km. For gasoline and methanol, this is 16–30% (Höhlein et al., 1999; Borroni-Bird, 1996; Thomas et al., 2000) and 23–37%, respectively (Ekdunge and Råberg, 1998; Höhlein et al., 1999; Klaiber, 1996; Thomas et al., 2000). Based on this we will use our calculated efficiency ranges as input for the well to wheel analysis.

### 3.4. Comparison of total fuel chains

Table 4 shows results for the complete fuel chains. The results are also stated in Figs. 3 and 4 for easy comparison of the fuel chains. They show energy efficiency and $CO_2$ emissions, respectively, for complete fuel chains in the probable case (Table 5).

From Fig. 3, it can be concluded that the diesel-hybrid combination consumes the least energy per vehicle kilometer, followed by two hydrogen-FCV chains. Combining the results in Fig. 3 with the earlier results in Tables 1 and 2, it can be concluded that the vehicle's efficiency has a very large effect on the total fuel chain efficiency. Except for the diesel-ICEV chain, the most efficient fuel chains are all innovative end use technologies (FCV and hybrid) compared to the current ICEV. Comparing Tables 1 and 2 shows that without the end-use stage, the NG chains are less efficient than the reference fuel chains. Only CNG and LNG have chain efficiencies that can compete with the reference chains. However, when the end use stage is added to the fuel chains the NG chains outperform most of the oil-based chains. In other words, a different type of end use technology (FCV) has to be involved in an alternative fuel chain to beat the reference case (ICEV) on efficiency. The hydrogen FCV is the most efficient vehicle, followed by the advanced diesel hybrid. The ICEV chains are clearly less efficient. The diesel-ICE vehicle chain has a very good ranking considering other ICEV cases.

Although the diesel-ICE-hybrid chain is most efficient, $CO_2$ emissions per kilometer are higher than when hydrogen is used as automotive fuel (see Fig. 4). The compressed hydrogen FCV chain is the most efficient fuel chain with respect to $CO_2$ emissions. The reason for this is that the conversion stage does not result in $CO_2$

Table 4
Efficiency of vehicles and fuel chain results

| Automotive fuel | Vehicle | Vehicle efficiency (%) | | | Fuel chain efficiency (%) | | | Energy consumption[a] fuel chains (MJ/km) | | | $CO_2$ emissions fuel chains (g/km) | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | Worst | Probable | Best | Worst | Probable | Best | Worst | Probable | Best | Worst | Probable | Best |
| Gasoline | ICEV | 15.0 | 18.0 | 20.0 | 11.0 | 14.8 | 18.0 | 3.7 | 2.8 | 2.3 | 269 | 199 | 165 |
| Diesel | ICEV | 17.0 | 22.0 | 24.0 | 13.6 | 19.4 | 22.6 | 3.0 | 2.1 | 1.8 | 219 | 153 | 132 |
| LPG | ICEV | 16.0 | 19.0 | 21.0 | 12.6 | 16.0 | 10.4 | 3.2 | 2.6 | 2.0 | 215 | 168 | 135 |
| FTdiesel | ICEV | 17.0 | 22.0 | 24.0 | 8.5 | 13.6 | 16.8 | 4.8 | 3.0 | 2.4 | 285 | 181 | 152 |
| CNG | ICEV | 16.0 | 19.0 | 21.0 | 12.6 | 16.5 | 20.4 | 3.2 | 2.5 | 2.0 | 198 | 150 | 120 |
| LNG | ICEV | 16.0 | 19.0 | 21.0 | 11.8 | 15.4 | 18.5 | 3.5 | 2.7 | 2.2 | 214 | 163 | 134 |
| Compr. $H_2$ | ICEV | 16.0 | 19.0 | 21.0 | 7.7 | 10.6 | 13.9 | 5.3 | 3.9 | 3.0 | 323 | 231 | 178 |
| FTdiesel | Hybrid | 21.0 | 28.0 | 30.0 | 10.5 | 17.4 | 21.0 | 3.9 | 2.4 | 2.0 | 230 | 142 | 122 |
| Diesel | Hybrid | 21.0 | 28.0 | 30.0 | 16.8 | 24.6 | 28.2 | 2.4 | 1.7 | 1.5 | 178 | 120 | 105 |
| Gasoline | FCV | 17.0 | 21.0 | 24.0 | 12.4 | 17.2 | 21.6 | 3.3 | 2.4 | 1.9 | 237 | 192 | 168 |
| CNG | FCV | 18.0 | 22.0 | 25.0 | 14.2 | 19.1 | 24.2 | 2.9 | 2.1 | 1.7 | 176 | 129 | 101 |
| Methanol | FCV | 21.0 | 25.0 | 30.0 | 9.2 | 16.3 | 20.7 | 4.4 | 2.5 | 2.0 | 275 | 154 | 118 |
| Compr. $H_2$ | FCV | 35.0 | 38.0 | 42.0 | 16.8 | 21.3 | 27.7 | 2.4 | 1.9 | 1.5 | 148 | 115 | 89 |
| Liquid $H_2$ | FCV | 35.0 | 38.0 | 42.0 | 8.8 | 12.9 | 21.4 | 4.7 | 3.2 | 1.9 | 276 | 183 | 111 |
| Local $H_2$ | FCV | 35.0 | 38.0 | 42.0 | 15.1 | 20.1 | 26.5 | 2.7 | 2.0 | 1.5 | 165 | 122 | 92 |

[a] This includes energy contained by the automotive fuel consumed by the vehicle and the energy to supply this amount of automotive fuel. The energy consumption per km by the vehicle is calculated using the assumption that 0.41 MJ/km is required as wheel power.

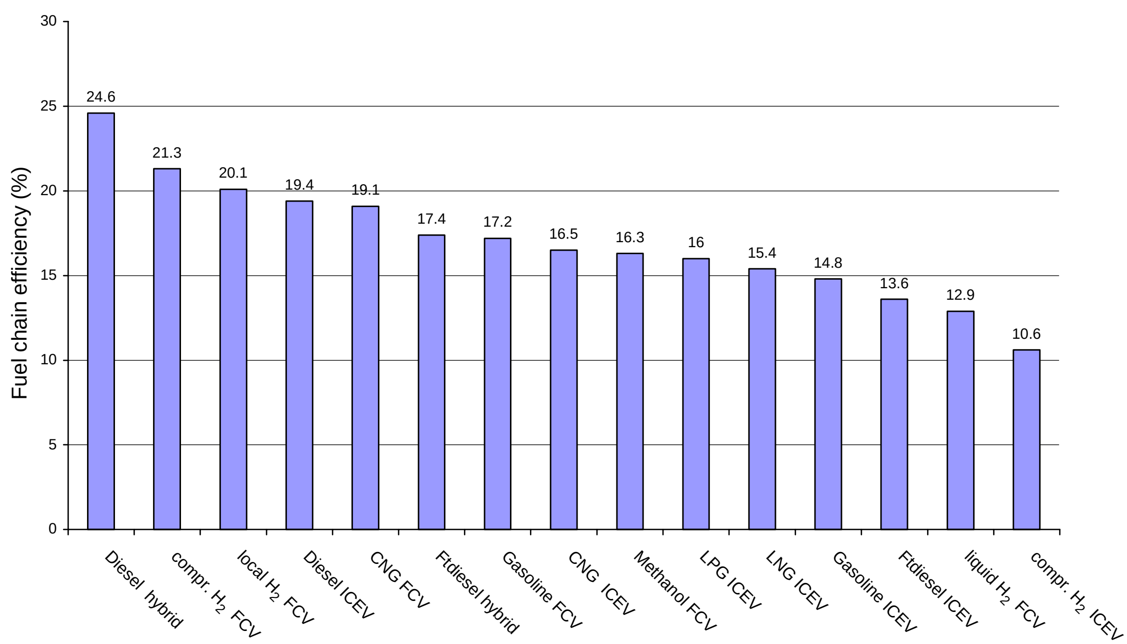


Fig. 3. Energy efficiencies of complete fuel chains for the probable cases.

emissions in the hydrogen chains, while it is this stage where most of the $CO_2$ is emitted in others. FCV end use makes up for high $CO_2$ emissions of fuel supply in the hydrogen chains. With $CO_2$ sequestration the hydrogen chains would even score better (see Table 4). However, when hydrogen is liquefied, the fuel chain carbon emissions rise dramatically. For hydrogen fuel chains to be beneficial with respect to $CO_2$ emissions, liquefaction should be avoided. Fig. 4 also shows that the most common fuel chain today, where gasoline is combusted in the ICEV, is one of the worst chains in terms of $CO_2$ emissions per vehicle kilometer. Just like it was the case for energy efficiency, NG chains achieve a good position in fuel chain ranking regarding $CO_2$ emissions due to a high FCV efficiency.

To sum up: clear winners are all FCV chains, except the gasoline FCV. Losers are all ICEV chains except the CNG-ICEV. The hybrid diesel fuel chain is the most efficient chain and also scores very well in terms of carbon emissions.

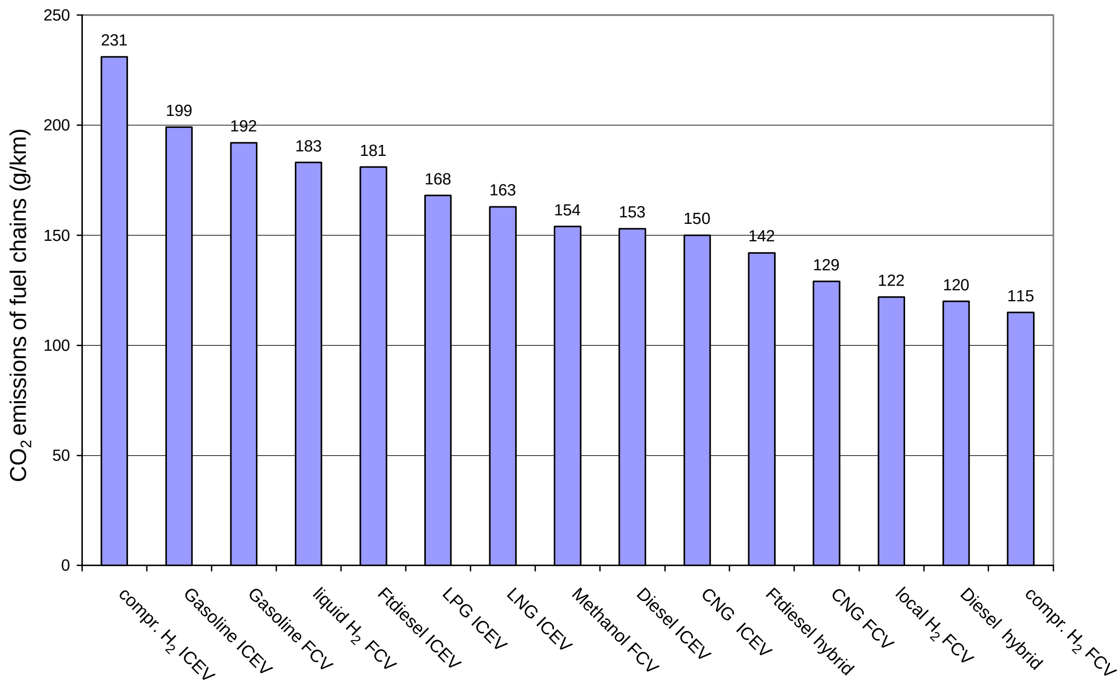


Fig. 4. $CO_2$ emissions of complete fuel chains for the probable cases.

Table 5
Amount of $CO_2$ produced by combustion of 1 MJ of process fuel

| Process fuel | $CO_2$ emissions (g/MJ used) | Efficiency production process fuel (%) | $CO_2$ emissions incl. $CO_2$ from process fuel production (g/MJ used) |
|---|---|---|---|
| Residual fuel oil | 79.3 | —[a] | 79.3 |
| Heavy fuel oil | 79.3 | 93[b] | 85.3 |
| Refinery still gas | 65.0 | —[a] | 65.0 |
| Diesel | 73.0 | 88[c] | 82.0 |
| Gasoline | 72.3 | 82[d] | 87.5 |
| Crude oil | 78.2 | 95[e] | 81.8 |
| Natural gas | 59.4 | 97[f] | 62.3 |
| Electricity | 0 | 45[g] | 132[g] |

[a] Produced within refinery by crude input, no extra primary energy input necessary.
[b] Crude extraction 95%, transport 99%, heavy fuel production refinery 99%.
[c] Efficiency total of the diesel fuel chain, see the results of diesel supply in Table 2.
[d] Efficiency total of the gasoline fuel chain, see the results of gasoline supply in Table 2.
[e] Crude oil extraction efficiency.
[f] Extraction of NG, usage of this NG near wellhead, transport not required, see Table 3.
[g] These numbers are used for calculations to give a projection for the situation the next two decades. Assumption: NG power plant, combined cycle, efficiency 53–55% (Wang, 1999) this becomes 45% including losses by transmission and distribution of 8% (Wang, 1999).

### 3.5. *Implementation barriers in the transition to alternative fuel chains*

In this section, we develop and apply a quick scan of the implementation barriers of the studied fuel chains. There appear to be many social and economic factors that influence the development and implementation of new technologies. Empirical studies of innovation and diffusion processes have shown that in many sectors innovations take two to three decades to diffuse to a significant extent (Karshenas and Stoneman, 1995; Grübler, 1997). The implementation of technical changes depends on both the characteristics of the technologies themselves and the characteristics of the socio-economic context in which they take place, the so-called 'innovation system'.

In Jacobsson and Johnson (2000) this innovation system concept is used to explain the diffusion characteristic of renewable energy technologies. Traditionally these innovation systems are often analyzed in a national context, the so-called national systems of innovations (Lundvall et al., 2002), but Jacobsson and Johnson (2000) use the concept of technology specific innovation systems to explain why a certain technology diffuses more rapidly than an other technology. In Johnson (2001) methodologies to assess the characteristics of these type of innovation systems are proposed. This approach should also be followed for a thorough analysis of the implementation barriers of the studied alternative fuel chains. However, to assess a single innovation system is already a large study by itself (Suurs et al. 2003). Assessing all the different innovation systems that are relevant in this study, due to the large number of fuel chains studied, was not feasible due to time constraints. Therefore we propose to make a quick scan of the implementation barriers by only focusing on the characteristics of the technologies themselves, which in our case are the alternative fuel chains.

To determine the characteristics of the fuel chains we discern two dimensions: the technical radicality of the innovation and the organizational complexity (required network change) of the innovation. The first dimension is defined as to which extend skills and expertise of organizations need to be adjusted to apply the new technology. An example of such a change is the switch of a manufacturer of steel parts to producing plastic parts. It either requires hiring new personnel with prior experience or education, or it requires considerable retraining of the current workforce. The second dimension concerns the change in the structure of the production and implementation network around an innovation. For example, a shift from combustion powered vehicles to electric vehicles requires changes in fuel supply and repair facilities in addition to the new engine components. Different firms than those involved in the existing system will often produce such supporting facilities.

To indicate the level of change on these two dimensions we use several concepts from the literature on innovation in terms of changes involved: incremental, radical, modular, and system innovations (Henderson and Clark, 1990; Tushman and Anderson, 1986). Incremental and radical innovations represent the dimension of technical complexity of new innovations while modular and systems innovations represent changes in the dimensions of networks. The two dimensions of change can be combined as innovations usually combine both technical and network dimensions (see Fig. 5).

Incremental innovations involve relatively small technical changes to existing products, refining previously used technology (Rogers, 1995). An example is direct injection of gasoline in ICEs, where air and fuel are no longer mixed before entering the cylinder. In contrast to incremental innovations, radical innovations are based on different engineering and scientific principles (Henderson and Clark, 1990). This may open up new markets and potential applications. Incremental innovation reinforces the capabilities of existing organizations while radical innovations forces them to ask a new set of questions, to draw on new technical and commercial skills, and to employ new problem solving approaches (Henderson and Clark, 1990). Therefore, the expected implementation barriers related to radical innovations are much larger than for incremental innovations.

Modular innovation resembles an innovation (which can technically be incremental or radical) that does not seriously affect the relationships or linkages between the actors involved (Henderson and Clark, 1990). A system innovation on the other hand requires many changes in the linkages between actors. The latter implies that multiple innovations have to take place at the same time and that different co-operating actors are involved. Using these concepts with respect to alternative fuel

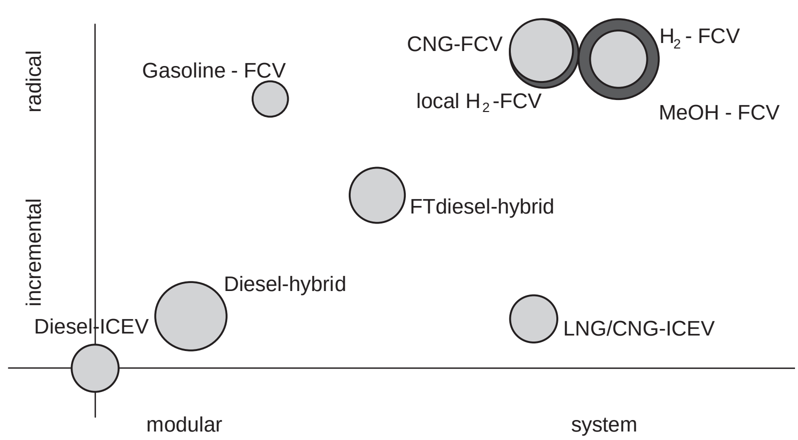


Fig. 5. Innovation characteristics of fuel chains based on technological changes (incremental→radical) and changes in socio-economic environment (modular→system) involved. Circle sizes indicate carbon emission reduction relative to gasoline-ICEV fuel chain. Darkest circles represent hydrogen chains.

chains, a change in one fuel chain component, not affecting links between components, can be regarded a modular innovation. An innovation affecting the whole fuel chain can be seen as a system innovation. The implementation barriers of a system innovation are perceived to be much greater than for a modular innovation.

Based on the above, the four types of innovations can be placed in the two-dimensional space drawn up by the dimensions: technological complexity of the innovation and necessary change in network (Goverse et al., 2001). Fig. 5 shows how alternative fuel chains are placed according to the characteristics of the innovations involved in relation to the conventional gasoline-ICEV fuel chain. In this figure, the areas of circles indicate how much $CO_2$ is saved with respect to the gasoline-ICEV fuel chain.

Using a diesel-ICEV already results in a reduction of $CO_2$ emissions in comparison to the gasoline-ICEV chain. This does not comprise additional innovations, and therefore this fuel chain is placed at the reference case position in Fig. 5. In a parallel diesel hybrid vehicle a battery is added to the conventional power train to store energy recovered from braking. Its introduction does not require changes in fuel supply since diesel can be the only energy input. This makes this innovation modular. Technically, this is an incremental innovation since the principles of the mechanical conventional power train remain the same in this vehicle, although the propulsion system is extended with an electrical drive.

An alternative where fuel supply remains unchanged is the fuel chain where gasoline is supplied and used by a FCV. The vehicle is the only component in the fuel chain changing with respect to the conventional fuel chain. However, the gasoline-FCV in which new technologies are applied to convert the gasoline into hydrogen and to generate electricity for the electric drive, is technically a radical innovation. This radical innovation also implies that the vehicle's power train is completely different, requiring completely new parts and maintenance. Furthermore, consumers will experience differences. Therefore, network changes will especially occur in the area of technology development stage and consumers. In terms of network change, this innovation is regarded to be in between modular and system innovation.

Production of FT-diesel using NG as a feedstock requires a totally different, but well-known, fuel production method. The last stages of the fuel chain, distribution and end use, are the same as in the conventional fuel chain. Therefore, this innovation is considered to have less systemic features than the other NG chains in which the infrastructure is dramatically different than today's infrastructure. Using a hybrid vehicle implies an extra incremental innovation with respect to the conventional ICE.

Implementing other NG chains changes fuel supply completely and multiple actors are involved. This results in system innovations. The fuel chains where LNG or CNG are combusted by the ICE do not require new technologies or distribution systems, and therefore technological changes are incremental. When CNG is used by a FCV, a radical innovation is involved as well.

The hydrogen, methanol and CNG FCV are all placed in the upper right corner of Fig. 5 suggesting both radical and systems change. We have already argued that a FCV is a radical innovation compared to an ICEV. Furthermore, for the $H_2$-FCV the distribution and storage of hydrogen require radical changes while in case of methanol and CNG the onboard reforming step require radical innovations. In term of system change all four routes require large changes in infrastructure. NG and methanol distribution will require fewer changes in current infrastructure than hydrogen. Also more new parties need to be involved to provide the necessary know how for hydrogen distribution and fuelling. Local production of hydrogen at retail stations takes place after CNG distribution. In this fuel chain additional changes are required at the retail station compared to the CNG chains.

## 4. Implications for managing the transition to sustainable transport chains

Fig. 5 indicates that the diesel-hybrid vehicle is the best improvement of the current ICEV in terms of $CO_2$ emissions and implementation barriers for the short term. The emission reduction is large and both the organizational and technical complexity is low. Does this mean that NG-based fuel chains are not suitable as transition technology to pave the road for long-term sustainable options? No, on the contrary. From Fig. 4 we have learned that two NG-based hydrogen FCV chains have very low $CO_2$ emissions compared to the current system and are comparable with the hybrid–diesel chain. However, Fig. 5 shows, that radical and system change is necessary, which implies that they are certainly no transition technologies for the short term. They are more suitable as medium term goals. The reason why these chains are so interesting is that they provide an excellent starting point for further greening of fuel chains. The sequestration of $CO_2$ when centrally producing hydrogen will dramatically reduce the carbon emissions of hydrogen chains. Also, in the long-term NG as feedstock for hydrogen production can be replaced by sustainable resources (biomass or green electricity). Based on this, NG-hydrogen chains are an interesting transition technology to a sustainable fuel system for the medium term.

To reach these NG-based hydrogen systems roughly two transition routes can be depicted (see Fig. 6). The

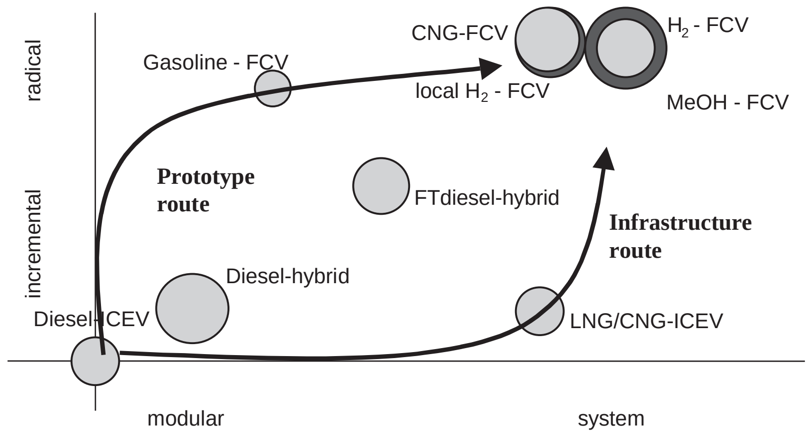


Fig. 6. Potential transition routes to NG-based hydrogen-FCV chains.

first route is called the proto-type route. In this case radical FCV innovations are developed and brought to the market that require hardly any change in infrastructure. In this case the gasoline fuelled FCV can be marked as transition technology. The other route is called the infrastructure route where first adaptations in the infrastructure are made, which are followed by radical innovations in vehicle technology on the longer term (taken from Lente et al., 2003). In this case the CNG-ICEV is marked as transition technology. In this situation NG is used as a short-term transition fuel before a switch to hydrogen as fuel may be made. The choice between the prototype and infrastructure route will be strongly dependent on the strategic moves of car manufacturers and energy companies. In the prototype case, the car manufacturers will have to innovate and take commercial risks while the infrastructure route will require investments from the energy companies. From an environmental point of view the infrastructure route is preferable since we classified the CNG-ICEV in Section 3.4 as a winner and the gasoline-FCV as a loser in terms of carbon emission reduction. So also in the short term the use of NG may be an interesting transition technology.

We like to finish the construction of transition strategies by comparing the diesel-hybrid-ICEV and the NG options. We regard the diesel-hybrid-ICEV as an important pillar in a transition strategy. It scores well in terms of $CO_2$ emission reduction, low implementation barriers and that it incorporates technology that can be used in follow up innovations like regenerative breaking technology and an electric drive train. On the longer term the diesel-hybrid-ICEV may be improved by using bio-diesel blends to lower carbon emissions. The analysis therefore does not lead to a single winner. Both the diesel-hybrid vehicle and NG-based hydrogen-FCV seem strong options for the future, either competing or in co-existence.

## 5. Conclusion

The main question in this paper is how much $CO_2$ emissions might be saved by implementing alternative fuel chains based on natural gas (NG) as primary fuel and whether these fuel chains may be part of a transition strategy towards sustainable transport fuel chains. Of the alternative fuel chains considered, NG-based hydrogen fuel chains reduce $CO_2$ emissions most. Compressed hydrogen used by a FCV may save carbon emissions over 40% with respect to the reference case. However, these hydrogen fuel chains are characterized as both radical and system innovations. Based on these characteristics, one cannot expect that the transition from our current transport chains to these innovative chains can be implemented without going through intermediate systems first. Two different transition strategies seem feasible. One based on developing radical end use technology first and then changing the fuel chains (proto type route), the other based on changing the fuel infrastructure before radical new automotive technology is brought to the market. In the first case, the gasoline-FCV is a potential transition technology while in the other case the CNG-ICEV is labeled as transition technology. The latter route is preferred from a $CO_2$ emission reduction perspective. The results show that NG is a very interesting transition fuel both in the short and medium term since more efficient chains can be based on the NG chains.

The results furthermore show that large $CO_2$ emission reductions can be realized by an innovation in the oil-based fuel chains. The diesel-ICE-hybrid chain leads to a $CO_2$ emissions reduction of 38% compared to reference system. We calculated this to be the second best option next to the NG-based hydrogen chains in terms of $CO_2$ emission reduction. The clear advantage of this fuel chain is that little implementation barriers are expected since the technology can be regarded as almost an incremental and modular innovation. For the short term, this fuel chain is regarded as an important improvement option for the traditional chains. We identify this technology as an important winner, also for the medium term since the performance can be further improved through the use of biomass as feedstock.

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