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Energy system aspects of natural gas as an alternative fuel in transport

ExecutiveSummary

NRW.

Preface

What kind of fuel will we use for our cars tomorrow? Considering the enormous ecological and economical importance of the transport sector this question touches upon a core element of sustainable development. The introduction of alternative fuels - together with drastic energy efficiency gains - willl be a key to sustainable mobility, nationally as well as globally.

The future role of alternative fuels can not be examined from the isolated perspective of the transport sector. Interactions with the energy system as a whole have to be taken into account. This holds both for the issue of availability of energy sources as well as for allocation effects, resulting from the shift of renewable energy from the stationary sector to mobile applications.

Such holistic assessments of alternative fuels, however, tend to be rare, more research is needed in this respect. The present study "Energy systems aspects of natural gas as an alternative fuel in transport" intends to contribute to the discussion. The research was commissioned by the Federal Association of German Gas and Water Industries (BGW) and the initiative erdgasmobil and it aims at investigating the future role of natural gas as an alternative fuel in relation to selected other fuel options.

The study puts its focus on energetic and climate policy criteria whereas economic parameters and business criteria could not be considered. The conclusions, therefore, primarily relate to societal benefits and strategic guidelines for policy-making and long-term technology development.

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Energy systems aspects of natural gas as an alternative fuel in transport
A report of the Wuppertal Institute for Climate Environment Energy

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Table of content

1 Alternative fuels - the key to mitigating the environmental impacts of transport

In all western economies vigorous activities aim at mitigating the environmental impacts of transport while reducing the risks of a geopolitical dependence on oil. The European Commission's White Paper A European Transport Policy for 2010, for instance, predicts a growth of European CO_2 emissions in transport by 50% up to some 1.1 billion tons for the period between 1990-2010. The White Paper comes to the conclusion that a viable way of reducing greenhouse gas emissions is the introduction of cleaner alternative fuels. This would also lower the present dependence of the European transport sector on oil, which is currently at 98%. The EU Commission has specified first political targets for the sector of road traffic, laying down that by the year 2020, alternative fuels should replace 20% of conventional fuels[1].

Natural gas and biofuels are seen as the most important short-term options for meeting these goals, whereas in the long run, a substantial contribution is expected to be delivered by hydrogen (H_2) and the fuel cell technology. The basic assumption here, that hydrogen is a clean energy carrier that under certain conditions is abundantly available, is gaining more and more political impetus, as growing budgets for related research show. The U.S. government, for example, recently announced planned investments of some 1.7 billion US$ in the FreedomCAR and Fuel Initiative set up to develop fuel cell cars powered by hydrogen and to establish the related H_2-infrastructure. Comparable activities can be found in Japan, and the EU is also intensifying efforts to prepare for the future hydrogen technology markets[2].

Key questions that often remain open, however, are how to deliver the hydrogen in a sustainable manner and in sufficient quantities, and how to integrate the new H_2 option into tomorrow's changing energy and transport infrastructures. From an environmental point of view, the abatement of local emissions related to transport, such as NO_x, VOC, particles, noise, etc., is not the only reason for promoting hydrogen[3]. An equally important challenge is the transformation of a transport system based on exhaustible resources to a system relying on renewable energy sources (RES), and, moreover, achieving a drastic reduction of transport-related GHG emissions.

For that reason, in the long run any sustainable hydrogen economy can only rely renewable energy sources. On the contrary, nuclear energy is not a sustainable option for generating hydrogen as it involves certain inherent technology risks. The question of nuclear waste disposal remains unsolved, and few societies fully accept nuclear energy. The large-scale use of fossil fuels in combination with carbon sequestration (e.g. coal gasification), where manifold technical, economic and ecological aspects remain unclear, is a highly questionable option, too. Even putative technological breakthroughs cannot extend the future potential of carbon sequestration beyond the limits of the availability of suitable reservoirs.

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[1] European Commission 2001a, 2001b, 2001c

[2] www.europa.eu.int/comm/research/energy/nn/nn_rt_hlg2_en.html; www.eere.energy.gov/hydrogenandfuelcells; www.enaa.or.jp/WE-NET

[3] European Commission 2003

However, it will take time to extend the capacity of clean RES for hydrogen production and establish an appropriate infrastructure. For the period of transition, therefore, bridging solutions with low environmental impacts and risks have to be found that allow using exhaustible resources more efficiently. In this context, natural gas can play a role – both as an alternative fuel for cars as well as a point of departure for a hydrogen economy.

2 Natural gas as a transport fuel – an energy system analysis

In the transport sector, natural gas can be used in different ways: as compressed gas (CNG), as liquefied gas (LNG) or in a processed form as synthetic diesel fuel (synfuel or gas-to-liquid GTL). Moreover, natural gas is the feedstock for the industrial production of hydrogen in methane steam reforming (MSR). Apart from the conventional sources for natural gas, biogenous methane (biogas or BCMG) can be used as primary energy.

Due to its technical fuel properties, the use of natural gas allows achieving significant reductions in local air pollutants and meeting the European EEV standard (Enhanced Environmentally Friendly Vehicle), which is well below the norms Euro IV and Euro V planned for introduction in 2008. In the present alternative fuel framework of the European Commission, natural gas plays a priority role. The aim is for natural gas to cover a share of 10% of the total final energy demand by 2020[4].

In Germany, the initiative erdgasmobil was established in April 2002 as a joint venture of the German gas industry and the oil companies that run the filling stations. It provides the framework for setting up 1,000 filling stations throughout Germany by the year 2006[5]. At the same time, the major car manufacturers increasingly offer CNG vehicles. Taking this perspective into account, natural gas is likely to gain importance as a fuel in Germany, especially if a long-term scheme of fiscal incentives ensures the economic attractiveness of the new option. In addition to other alternative fuels, natural gas will contribute to a diversification of the transport energy supply.

What, however, will be the implications of these changes for the energy system and energy infrastructures? Careful consideration will have to go into the relation of natural gas to other new options, and particularly to hydrogen:

- What is the future role of natural gas in the transport sector, what emissions reductions can be achieved?
- What are the options for using natural gas as a vehicle fuel? How does CNG compare to synthetic diesel (GTL) and biofuels?
- How does an introduction of hydrogen impact the energy system? What paths of market entry (until 2050) are sensible from the point of view of energy supply and the environment?
- What time frame results for natural gas, and what is the role of natural gas in the introduction of hydrogen?

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[4] COM(2001)547Final, see EG (2003)

[5] www.erdgasfahrzeuge.de

Against this background the present study offers an energy system analysis of natural gas as an alternative fuel. Emphasis was placed on the impacts on energy demand and the related GHG emissions. Economic aspects such as production costs are beyond our present scope. Moreover, a sound analysis of costs is hardly feasible at the current state of technology. Most options are still at the beginning of their development, and future R&D may be expected to yield significant improvements which, in turn, will affect costs. On the other hand, R&D activities strongly rely on public support and the future policy framework. The latter will have to take the ecological impacts into account, so that the discussion of aspects of energy and ecology provides a basis for the exploration of politically desirable and economically robust future markets.

The study focuses on the fuel options that are most relevant in the current debate in Germany. A close examination of further fuel options especially in the wide field of biofuels as well as some alternatives for H_2-production is beyond our present scope[6].

3 Background and methodology

The introduction of alternative fuels will require significant, long-term investments for setting up and expanding infrastructures. This is especially true in the case of a hydrogen economy based on renewables. Today's decisions, therefore, should be oriented toward robust options with stable prospects even under changing future framework conditions. Long-term scenarios are one tool for finding robust options because they allow outlining future developments of energy systems in relation to a variety of framework conditions and policy settings. These scenarios refer to the total energy system so as to provide a complete balance of energy consumption and GHG emissions, and to take shifts between different sectors into account.

The present study builds on a recent long-term scenario assembled by the German Environmental Agency (Umweltbundesamt, UBA). Its analysis of the energy system provides the basis for our more detailed investigation of the transport sector[7]. Its high relevance to the fuel problem makes the sector of private passenger cars, i.e. vehicles of up to 2.8 t weight, an ideal example for discussing the impacts of different strategies of introducing alternative fuels. Comparable analyses are possible for all remaining sectors and can be extended to a European perspective.

3.1 Specific GHG emissions of fuel chains

A full assessment of the energy- and ecological aspects of the various fuel paths requires an evaluation of conversion efficiencies and specific emissions along the entire fuel process chain. First, this concerns fuel processing from the primary energy source to the vehicle, i.e. the specific GHG emissions per unit of final energy [g CO_2eqv/MJ]. The specific emission factors used in the study for the selected fuel pathways are depicted in Tab. 1[8]. In the case of

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[6] The possible use of excess hydrogen from industrial processes has not been studied.

[7] Fischedick, Nitsch et al. 2002

[8] Based on GM Well-to-Wheel Analysis of Energy Use and Greenhouse Gas Emissions of Advanced Fuel/Vehicle Systems- A European Study (LBST 2002a); data correspond to the best estimates mentioned here. Recent research by CONCAWE, EUCAR and JRC in the framework of the EU Commission's Alternative Fuels Contact Group and the options discussed there could not be taken into account.

renewable energy paths it has to be kept in mind that these values are seen from the perspective of the transport sector only and do not take systemic effects into account (cf. chapters 4.3. and 5.2).

Tab. 1: Selected emission factors of alternative fuels

Specific GHG-emissions	Fuel chain	Vehicle emissions[1)]	Local CH_4 and N_20 emissions[2)]	**Total**
	[in g CO_2eqv/MJ]			
Gasoline	13.2	73.4	2.4	89.0
Diesel	10.4	72.8	1.7	84.9
FT-diesel (remote gas)	28.0	71.0	0.0	99.0
Biodiesel/RME[3)]	-48.0	76.7		28.7
FT-Diesel (biomass)	-62,0	71,0		9,0
CNG 250bar[4)]	14.0	56.4	2.4	72.8
CNG (via LNG)	16.0	56.4	2.4	74.8
CMG 250bar (fermentation)	-56.7	56.9		0.2
CGH_2 700bar (EU gas, dec. MSR)	103.0	0.0		103.0
CGH_2 700bar (waste wood gasification)	7.0	0.0		7.0
CGH_2 700bar (Wind power, decentral. electrolysis)	0.0	0.0		0.0
LH_2 (MSR)	124.0	0.0		124.0
LH_2 (Wind power, central electrolysis)	2.0	0.0		2.0

Source: LBST 2002a
Negative values count for carbon content of biomass input.
Renewable energy paths are seen from the transport sector and do not reflect systemic effects.
1) CO_2 content of fuel
2) conventional drive trains
3) best estimate for RME (11.5 – 77.9 g CO_2eqv/MJ)
4) supply from EU mix

Second, the total emissions of a fuel pathway are strongly affected by the propulsion technology that converts fuel to motion on board the vehicle. The efficiencies of the Otto engine, the diesel engine, the hydrogen internal combustion engine or the hydrogen fuel cell can differ quite significantly. The values for conversion efficiency [MJ/km] of the selected propulsion technologies are depicted in the appendix.

3.2 Specification of the analytical frame

Regardless of any alternative fuel, energy demand and GHG emissions of the whole vehicle fleet will change. Important driving factors are overall car use (kilometres per person and year), progress in vehicle technology and a changing mix of vehicle types in the total fleet.

Independently from the discussion on alternative fuels, therefore, two lines of development of the average energy consumption of cars between 2000 and 2050 are defined:

- Consistent with current trends it is possible to assume that average fleet consumption will drop by a range of 43% (diesel) and 57% (fuel cell vehicle) between 2000-2050. This **trend** projection builds on a foreseeable variety of improved technologies including aerodynamic improvements, lightweight construction, a demand shift toward smaller cars, etc.[9]. Even without a significant replacement of gasoline and diesel with alternative fuels, these reductions in specific fleet consumption will induce significantly lower GHG emissions. This **business-as-usual case (BAU)** will lead to a decrease of emissions from 135 million tons CO_2eqv in the year 2000 to 78.3 million tons CO_2eqv in 2050.
- This, however, falls short of an ambitious **sustainability** target, i.e. a reduction to 30.4 million tons CO_2eqv by 2050 that is based on the UBA sustainability scenario, which calls for an 80% reduction of total GHG emissions between 1990 and 2050. Meeting this goal without any contribution from new fuel options would require a reduction of average fleet consumption by some 80% by 2050 compared to 2000 – no doubt an enormous challenge. A **high-savings** case was therefore outlined to describe an extreme development where a combination of all kinds of energy saving measures results in an average fleet consumption of around 2 litres gasoline/100 km by 2050.

  In spite of its drastic implications, however, this scenario is by no means an unrealistic utopia. The long-term target definition builds on scientific conclusions as are embraced by the Intergovernmental Panel on Climate Change (IPCC) when it demands efforts to limit the impacts of global climate change within "a tolerable range." In the short- to mid-term, the intermediate targets of this reduction pathway correspond to Germany's international commitment within the Kyoto Protocol (reduction of GHG emissions by 21% for 2008-2012), and they reflect the range of targets currently discussed at national levels. For the year 2020, both the German Environment Ministry and the German Government Council of Experts for the Environment[10] request cutting GHG emissions by 40 % compared to 1990.

These two outlines specify the scope of action in a world without alternative fuels: assuming a progress in energy efficiency according to trend, the resulting GHG emissions will only decline to the business-as-usual level, i.e. the long-term requirements of climate protection will not be met. In order to reduce GHG emissions sufficiently to comply with sustainability targets, an extraordinary boost of energy efficiency according to the high-savings case will be needed.

So what is the contribution of alternative fuels to mitigate this dilemma? The present study offers a more thorough investigation of the impacts of an introduction of alternative fuels on energy demand and GHG emissions. Taking the sector of private passenger cars as an example, we took the possible shares of different fuel options as variables and analysed the effects in the BAU and sustainability cases, respectively (cf. Appendix for the methodology).

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[9] LBST2002b, Dauensteiner 2002, Petersen, Diaz-Bone 1998

[10] Rat von Sachverständigen für Umweltfragen der Bundesregierung (SRU), Sondergutachten 2002

The key question was whether an increased share of any specific alternative fuel would result in additional contributions to GHG reduction, as compared to the BAU case. In how far is it possible to move toward the emission levels of the sustainability case without having to squeeze the specific energy consumption of the vehicle fleet as drastically as in the high-savings case? Can the use of alternative fuels relieve some of the pressure on the need for energy efficiency measures?

4 The prospects of natural gas as an alternative fuel

4.1 CNG: Contribution to emissions reduction and bridging technology for hydrogen

Current activities to establish a network of natural gas filling stations in Germany focus on the provision of compressed natural gas (CNG), which is used in vehicles with modified Otto engines. The specific GHG emissions of the CNG fuel chain are 72.8 g CO_2eqv/MJ, i.e. lower than for diesel (84,9 g CO2eqv/MJ) and gasoline (89 g CO_2eqv/MJ) (Tab. 1)[11]. Compared to the conventional gasoline-driven Otto engine, a reduction of some 18% can be achieved. The advantage compared to diesel is smaller (14%). At present, however, these fuel related advantages of CNG can not be fully realised due to a lower conversion efficiency of CNG engines, especially compared to the diesel engine. However, considering the untapped potentials for optimising the CNG engine, further improvements may be expected to come close to the diesel engine. One example are current R&D activities in the field of heavy goods vehicle engines[12]. In view of the political targets set up in the EU and the resulting impetus for the CNG market, therefore, there is an urgent need for car manufacturers to supply optimised CNG engines for all vehicle types.

What would the impact of an extensive introduction of CNG vehicles be? Taking as an example the EU Commission's target to increase the share of CNG vehicles in the total fleet to 10% by 2020, this would yield a reduction of GHG emissions by about 2% compared to the BAU case (77 million tons in 2050 vs. 78.7 million tons, Fig. 1). So as long as fleet consumption remains consistent with current trends, the contribution of CNG to climate change mitigation is positive, though the quantitative effects are limited. In the hypothetic case of a 100% coverage of CNG cars, GHG emissions would decrease to 64.5 million tons CO_2eqv, i.e. –18% compared to BAU. Assuming the input of bio-methane (BCMG) instead of CNG to the 10% share of vehicles, emissions will decline to 70,5 million tons CO_2eqv, emphasising the ecological attractiveness of biomass pathways (cf. chapter 4.3)

A reduction of GHG emissions in the order of the sustainability case cannot be achieved by a shift to CNG alone. Average fleet consumption also has to decline along the high-savings line. This first result underlines the need for manufacturers to take action to provide highly efficient propulsion technologies and car concepts – which would in turn increase the driving range of CNG vehicles.

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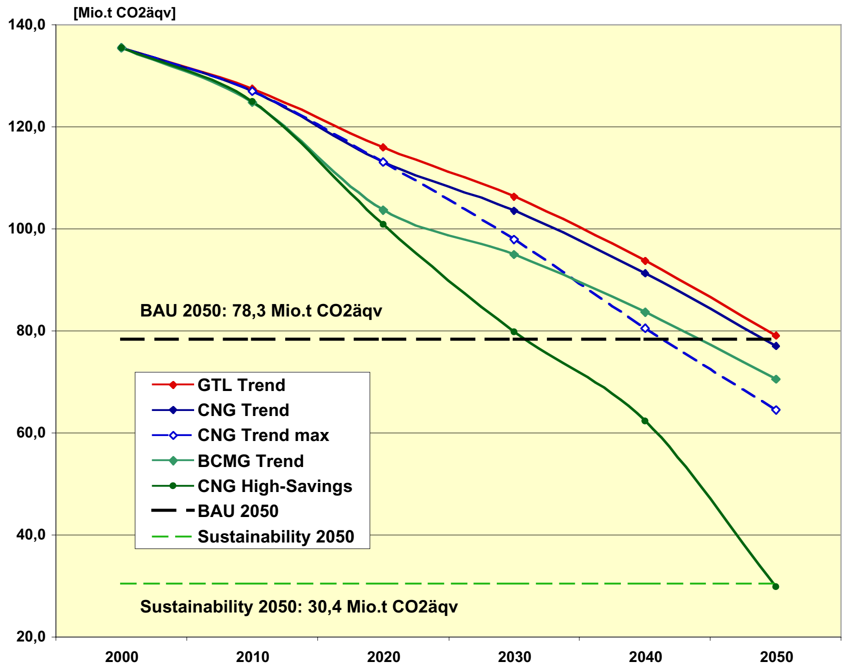
[11] The values refer to a supply from the EU gas mix. When considering a growing share of supply from sources in Russia additional impacts need to be taken into account. However, in order to provide a sound assessment of changing supply patterns a profound analysis of the Russian gas industry including most recent studies would be necessary but beyond the scope of this study.

[12] BWK 2002

Fig. 1: GHG emissions 2000-2050 for selected natural gas pathways



The introduction of CNG comes with a side benefit that may gain importance in the long term. This is an infrastructure of filling stations for compressed gas that can also serve a future hydrogen economy. The ecological assessment of the various fuel paths yields the conclusion that both for natural gas and hydrogen, the compressed gas paths cause fewer conversion losses than liquefied gas pathways. From the perspective of climate change abatement, a large-scale compressed gas pathway appears to be preferable to the liquid gas option (cf. chapter 5)[13]. Synergy potentials can be found in all aspects of the handling of compressed gas[14], from technologies for distribution and dispensation to on-board storage to the integration of high-pressure tanks into platform design[15]. In addition, socio-economic aspects include a gradual creation of acceptance on the part of end-users who need to get used to handling compressed gas – an essential precondition for a hydrogen economy.

4.2 GTL: No energetic and ecological advantages compared to CNG

The option of converting natural gas into synthetic diesel through a Fischer-Tropsch synthesis is increasingly being discussed by such companies as Shell, BP and VW (*FT-diesel*, *Synfuel* or *gas-to-liquid GTL*)[16]. Oil companies emphasise the opportunities offered by GTL technology, to exploit natural gas resources that are beyond the reach of pipeline

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[13] From a technical and business point of view, however, the LH_2-Option may offer certain advantages that impede a precipitate exclusion of options.

[14] In the long-run one could even think about using the natural gas grid for transport and distribution of hydrogen from central production (LBST 1994)

[15] Krüger 2003

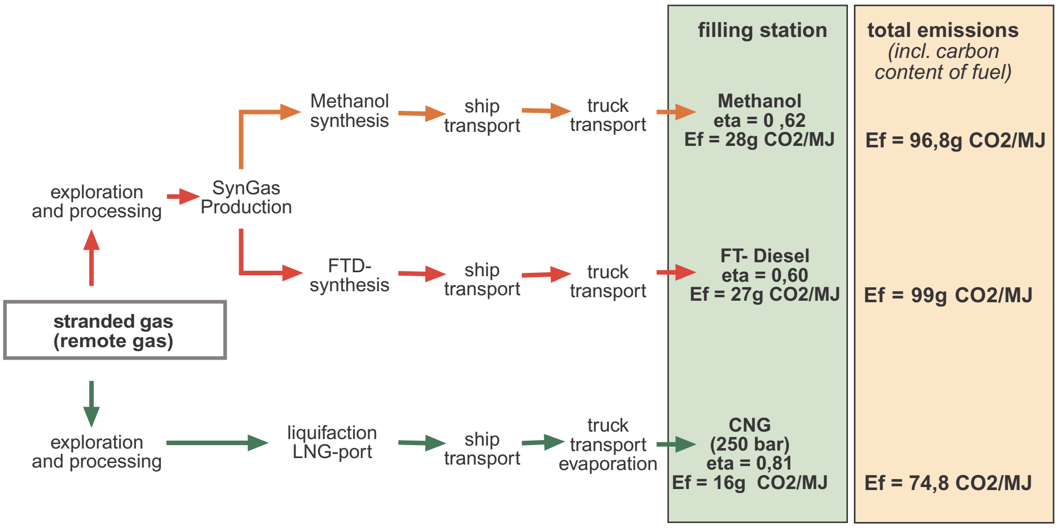
[16] Steger, Warnecke, Louis 2003, Lounnas, Brennand 2002, Mackenzie 2000

infrastructures (remote or stranded gas). The final GTL product could be processed, transported and distributed like any other conventional liquid fuel by using the existing refineries and filling stations. From a carmaker perspective, GTL offers the advantages of a fuel ideally suited to the needs of a future generation of diesel engines that are heading for significant efficiency gains and emissions reductions.

The question is whether synthetic diesel fuel made from natural gas represents a superior alternative to the CNG pathway. A closer look at the fuel chain gives reason to doubt this:

- From an energy and climate perspective, the evaluation is straightforward: Over the complete process chain, GTL has higher conversion losses than the CNG option. This holds even in the case of an exploitation of remote sources that require the gas to be liquefied in an intermediate step. The specific emissions of GTL are 99 g CO_2eqv/MJ, i.e. one third higher than in the case of CNG (72.8 g CO_2eqv/MJ) and CNG with intermediate LNG phase (74.8 g CO_2eqv/MJ) (Tab. 1 and Fig. 2). As already mentioned the GTL diesel engine still offers a higher efficiency than the CNG engine but the latter offers the prospect of approximating to its competitor. Relating these figures to the example of a 10% share of the total fleet and assuming a comparable efficiency, a use of GTL would in 2050 induce emissions of 79.1 million tons (+2.7% compared to the CNG path, Fig. 1). Compared to the BAU case (78.7 million tons in 2050) there is even a net increase. The overall effects still remain small in quantities but they show a clear tendency. A higher share of gas vehicles would amplify these effects in proportion.

Fig. 2: Overview of process chains for the use of remote gas as a fuel



remark: eta - conversion efficiency
Ef - specific emissions

source: LBST 2002a

- Due to the disadvantage in GHG emissions a production of GTL in Germany and Europe from natural gas provided by the European gas grid does not make sense. Even in the case of remote gas sources, the GTL option does not offer any fundamental advantages because these reservoirs could also be exploited through liquefaction of gas (LNG) and transport in tankers. A closer look, however, should be given to the question whether in the long-run minimum thresholds in plant size and capacity might limit the applicability of technologies.
- In the end, it will be economic factors that determine any final decision for the GTL option. Furthermore, tshere might be a time advantage for GTL due to the already existing global infrastructures for a liquid fuel. This might become a compelling argument when short-term reductions of local emissions are requested for areas with insufficient gas infrastructures such as boom regions in Asia. In any case, the future development of markets for GTL and LNG will be strongly affected by regional conditions and costs at the production site. Concerning GTL technology costs, potentials for cost degression can be found. However, the same holds for the LNG case, where a dynamic growth of global markets will trigger technical progress. On the contrary, the economic potential of GTL in the global markets for middle destillates depends on future energy prices and especially on the relative spread of oil and gas prices. All in all, a generic economic advantage of GTL over LNG/CNG can be questioned[17].

4.3 Bio-methane as an option for reducing GHG emissions on the natural gas pathway

Natural gas offers several advantages as a fuel and is immediately available. Nonetheless, it is subject to the same restrictions as any other limited fossil fuel. In the long run, these fuels need to be replaced by renewable energy sources (RES) and meanwhile have to be used efficiently. For that reason, it makes sense to test in how far renewable sources can provide natural gas, i.e. methane. “Greening the gas industry” is the battle-cry here, and biogenous methane (bio-methane) may turn out to be as important as RES hydrogen. There are various options for producing bio-methane:

- Bio-methane can be produced from **wood-type biomass** via gasification and a methane reaction that replaces the FT synthesis of the corresponding FTD process to produce liquid biofuels (bio-FTD)[18]. So the GTL pathway is not the only possibility of using solid biomass as a fuel[19]. From a theoretical and technical perspective, there are no major obstacles to establishing a bio-methane path comparable to the BTL option. The process for turning solid biomass into methane, however, is still under development, while industrial demonstration activities are being undertaken in the case of bio-FTD. A time lag of 10-15 years and the resulting need for intensive R&D characterise the situation for bio-methane in this field.

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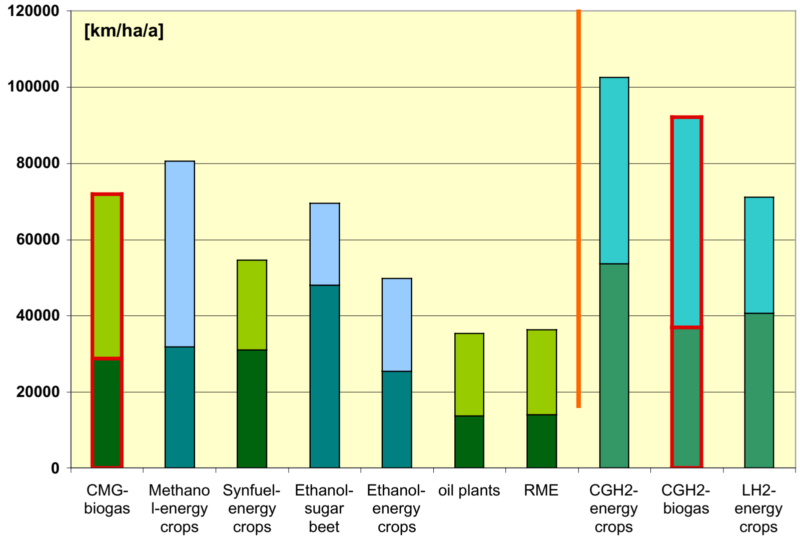
[17] Bakhtiari 2002, Zeus Development Corporation (2003)

[18] Often called biomass to liquids (*BTL) or Sunfuel*, *Biotrol* etc..

[19] Cf. Stucki et al. 2003, Mozaffarian, Zwart 2002, Stucki, Biollaz 2001, den Uil et al 1998

- Agricultural land can be used for the production of rapeseed (biodiesel, RME) or Ethanol as well as for the **cultivation of energy crops**, especially certain types of grass, for fermentation and biogas production. At the moment, these options are receiving little attention, but first assessments promise a potential that significantly exceeds the one for conventional biodiesel (Fig. 3, CMG biogas vs. RME)[20]. Moreover, it appears that certain negative impacts of the intensive cultivation of oil seeds can be mitigated. Comparative systems analyses are required to evaluate the broad range of impacts and interactions and to investigate in further detail how to use the limited surface for biomass production without harming the ecological balance.
- In addition, bio-methane will be available from **conventional biogas sources**, i.e. the fermentation of manure and organic waste, as well as sewage plants and land fills.

Fig. 3: Comparison of fuel potential of selected biofuels from cultivation of energy crops



remarks: specific output per hectar converted to annual driving range of a reference vehicle (Opel Zafira), using various drive trains:
- input of CGH_2 in fuel cells
- methanol and ethanol in fuel cells with on-board reforming
- CMG, Synfuel, oil and REM in diesel engine

source: Schindler, Weindorf 2003

Given that an efficient process for gasification and methane production on an industrial scale can be developed, an additional potential of some 400 PJ/a could complement the existing biogas potential from fermentation of 356 PJ/a. The estimated overall potential for bio-methane is likely to be 760 PJ/a, i.e. roughly 20% higher than the potential for bio-FTD (615 PJ/a) (Fig. 4). These orders of magnitude, however, can only be seen as first indications, and the figures are strongly affected by the underlying assumptions concerning conversion

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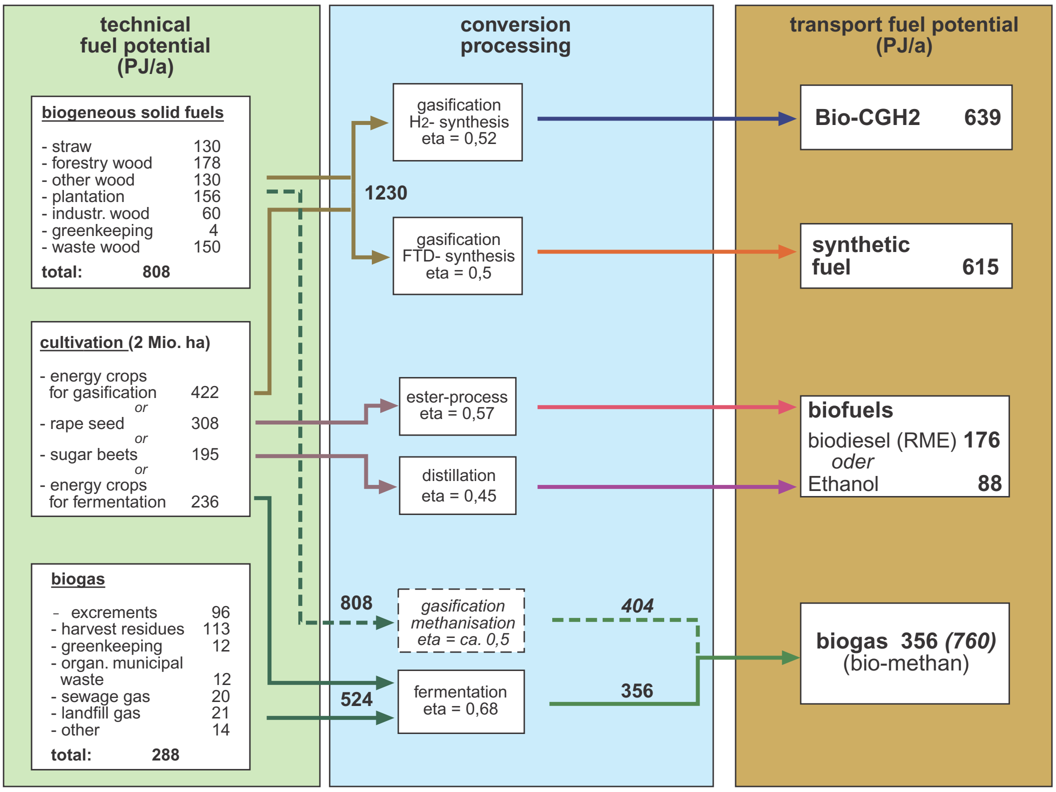
[20] Schindler, Weindorf 2003

processes[21]. Furthermore, it has to be checked how much of the biomass feedstock is at all available for fuel production. In the case of waste wood in Germany, for example, the major part is already being consumed by large biomass power plants.

Fig. 4: Estimation of potentials for selected biofuels



remarks: due to overlapping biomass inputs the potentials derived can not be added

source: - for technical fuel potential: Kaltschmitt 2003
- für conversion efficiencies: LBST 2002a

The production of biogas and its use in stationary applications for heat and electricity generation is state of the art. It is expected that this market will gain further relevance in Europe during the coming years[22]. The use of bio-methane in mobile applications, however, hardly plays a role. Nonetheless, it offers an interesting option for reducing GHG emissions along the CNG path (cf. Fig. 1). Examples from Sweden and Switzerland illustrate how large-scale distribution supports the introduction of biogas at filling stations or bus depots. As in the case of “green” electricity, clean and refined biogas from fermentation and gasification could

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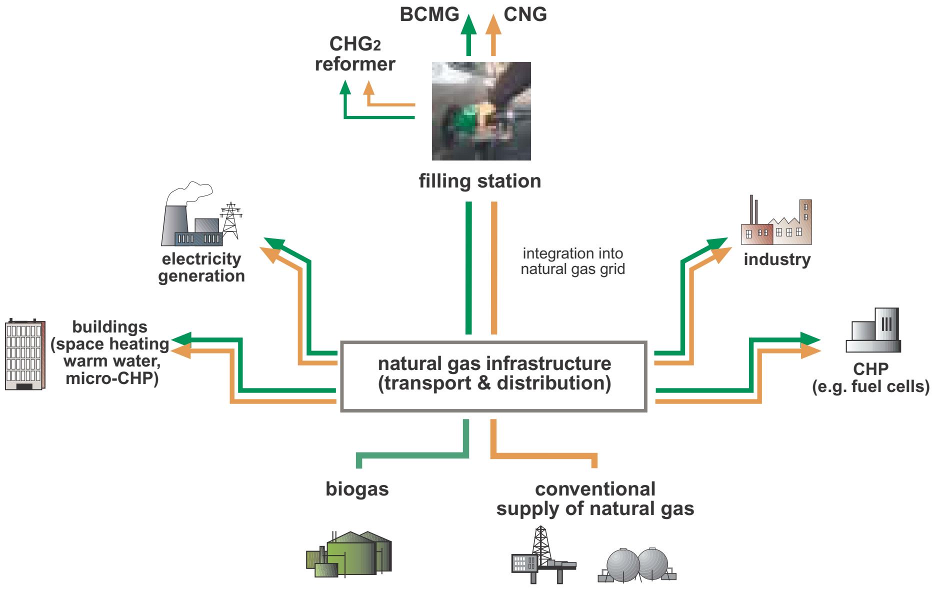
[21] The estimations strongly depend on the underlying assumptions concerning the efficiency of conversion processes. According to the operators, for example, the Choren FTD-Synthesis is likely to achieve a total efficiency of 75% whereas in the case of bio-methane estimates of future efficiencies are as high as up to 80%. Complete and proven energy balances of real demonstration projects would offer the opportunity to obtain profound conclusions but are still lacking.

[22] French 2003

be fed into the existing grid and distributed through the natural-gas pipelines (Fig. 5)[23]. Close cooperation between producers, the gas industry and end users can overcome a situation in which the use of biogas is restricted to the immediate vicinity of the production site. An economically attractive exploitation of bio-methane will require both cost-effective technologies for cleaning and up-grading biogas as well as a reliable framework for the commercialisation and marketing of the ecological added value of bio-methane.

Fig. 5: Enhanced use of biogas through feed-in and distribution in the natural gas infrastructure



Source: Based on Schindler, Weindorf 2003

Any assessment of biomass potentials, however, has to take into account that there are multiple and often competing applications. Next to use as fuels for transport, biomass can serve to generate heat and/or electricity or provide industrial processes with renewable materials. With regard to the cultivation of energy crops, there is a growing demand for organic agriculture as well as nature conservation. A holistic and dynamic assessment of these potentials that takes the various interdependencies into account in an encompassing systems analysis has yet to be compiled. Far more research is needed. Nonetheless, the case of biofuels looks promising, especially compared to their current use in fairly inefficient biomass power plants without heat use. A quantitative estimate of such allocation effects is given in chapter 5.3, taking the input of RES electricity for hydrogen electrolysis as an example.

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[23] Schindler, Weindorf 2003, Schulz, Hille 2003

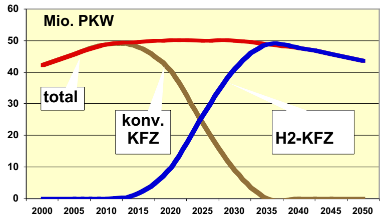
5 The introduction of hydrogen as a new fuel

A common consensus is that the vision of a solar hydrogen economy should be realised in the course of the 21st century. Divergent views, however, can be found once it comes to the short to mid-term strategies. World-wide, a common approach to market introduction is still lacking.

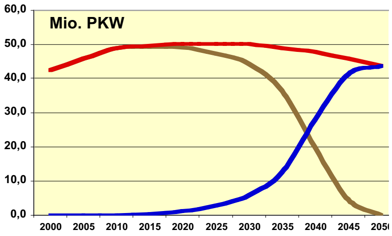
Depending on how fast the share of H_2 vehicles grows, the impacts on final energy consumption, the energy demand for hydrogen, and the resulting GHG emissions will differ. From the perspective of natural gas as an alternative fuel, another interesting question concerns its role in hydrogen production. The key issue here is at which point in time it makes sense for hydrogen actually to substitute natural gas.

Three pathways have been outlined for the analysis of the impacts that the introduction of hydrogen has on the energy system. They vary in terms of the share of H_2 vehicles over time:

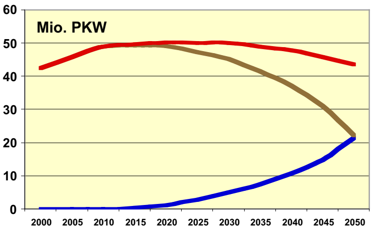
- A **forced introduction** pathway is based on the assumption that a 100% coverage of hydrogen vehicles will be realised between 2010-2035. This path reflects an extreme case with politics and industry pushing ahead the H_2 strategy at top speed.



- The **streched introduction** describes a slower, but nevertheless complete introduction of hydrogen between 2010 and 2050.



- The **moderate introduction** leads to a share of 50% of hydrogen vehicles by 2050 (beginning in 2010), which is considered to provide a sufficient foundation for achieving a hydrogen economy some time after 2050.



These three pathways illustrate very different approaches to a hydrogen system. They are no prognoses or market studies. On the contrary, their purpose is to outline possible futures and provide a basis for a discussion of the impacts that different modes of hydrogen production and use have on the energy system and the ecosystem. As a striking observation, until 2030 the stretched and the moderate introduction follow the same path, i.e. for a certain time the same strategy will keep the flexibility to end up at two quite different levels.

5.1 The key question: Where does the hydrogen come from?

The use of hydrogen as a fuel has the advantage that hydrogen-driven vehicles will produce hardly any emissions but vapour. The energy inputs and major ecological impacts of hydrogen production, transport and distribution are to be found in the fuel chain, which therefore needs to be submitted to closer scrutiny.

Conventional hydrogen production through methane steam reforming (MSR) causes specific emissions of 103 g CO2eqv/MJ, i.e. a factor 8,4 higher than the gasoline/diesel fuel chain. As the fuel cell propulsion system promises to be some 30-40% more efficient than the conventional ICE, an overall (*well-to-wheel*) reduction of GHG emissions takes place. In the case of stretched introduction in combination with improvements in fuel cell vehicle efficiency consistent with the trend line, the MSR path will lead to a decrease of GHG emissions by nearly 8% compared to the BAU case (72.6 million tons vs. 78.7 million tons by 2050) (Fig. 8 on page 19). In a scenario that ignores the issue of resource availability in the phase of transition, the use of natural gas as a feedstock for hydrogen production will induce slightly positive effects without substantially contributing to the ambitious targets for climate change mitigation.

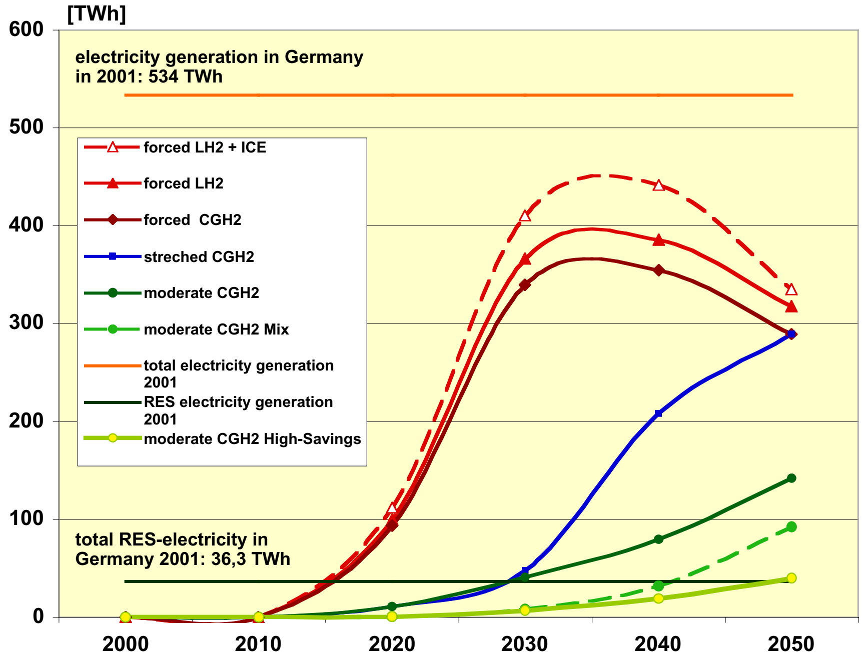
In the long run, hydrogen production based on fossil energies is not an option. For implementing a climate-friendly and sustainable hydrogen system it will be essential at what time and to what degree renewables can cover transport-related energy demands. RES, however, cannot be examined from the isolated perspective of the transport system. Interactions with other areas need to be taken into account. A holistic energy system analysis reveals that the near future is rather less bright where hydrogen is concerned:

- Assuming progress in vehicle technology consistent with current trends, even the stretched introduction induces a demand for compressed hydrogen (CGH_2) of some 700 PJ in the year 2050. Taking into account the conversion losses for electrolysis and compression, the required amount of renewable electricity reaches 289 TWh (Fig. 6), which corresponds to more than 50% of total electricity generation in Germany in the year 2001 (534 TWh) and exceeds the current production from RES (36,3 TWh in 2001) by more than seven times. It will not be easy to deliver this amount. Comparable obstacles arise for the use of biomass as the primary energy source for hydrogen. Even a full – unrealistic - exploitation of the biomass potential in Germany for H_2 synthesis will deliver only 639 PJ bio-CGH_2 (cf. chapter 4.3).
- In the forced introduction case, hydrogen will be needed much earlier to reach a 100% share in 2035. Several driving factors that diminish energy demand after 2030 such as declining population, more efficient cars, etc. do not yet come to bear at this point. Energy demand accordingly rises to an intermediate peak of 850 PJ H_2 and approx. 355 TWh RES electricity in 2040.
- The retarded moderate introduction represents a share of 50% in 2050 and thus leads to a lower energy demand for hydrogen (346 PJ H_2) and RES electricity (144 TWh) in 2050. Compared to today's level, however, even these figures require an increase in RES capacity by three or four.
- The demand for RES electricity decreases further if hydrogen is produced not only through electrolysis but in a generation mix. Assuming an initial 100% coverage by MSR followed by a growing share of RES electrolysis reaching 60% in 2050, the

maximum demand for RES electricity is 90 TWh in 2050. If the high-savings path materialises, only 40 TWh will be needed. These figures are in a much more realistic range.

- Compared to compressed gas hydrogen (CGH_2), additional losses occur in the case of hydrogen liquefaction (LH_2), which induces an additional demand for RES electricity. In the forced introduction case, the maximum for LH_2 will be reached in the year 2035 (386 TWh, i.e. +23% compared to the CGH_2 path). Compared to the CGH_2+fuel cell option, even more losses occur when using LH_2 in an internal combustion engine, raising the maximum to 440 TWh in 2035 and surpassing the CGH_2 case by 40%[24].

Fig. 6: Overview of hydrogen pathways and the resulting demand for RES electricity



Theoretically, the potentials for producing the required amount of RES electricity do exist. But it is quite unrealistic to suppose that they can be fully exploited. Even with a mix of different RES, it will hardly be possible to reach the required capacities in so little time, especially since other end-use sectors increasingly call for RES, too.

These limits to growth can be illustrated by the case of wind power, which is commonly regarded as the most promising and fast-growing RES option. Assuming a load factor of 2000h/a, the demand of 290 TWh (stretched introduction) corresponds to a capacity enlargement by 145,000 MW. Consider, as a comparison, that in 2001 the complete power park in Germany added up to a total capacity of 102,000 MW. In the case of a moderate

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[24] Recently, BMW announced a significant improvement of the hydrogen ICE (BMW 2003)

introduction and a hydrogen generation mix, in contrast, a demand of 90 TWh has to be met. This equals a wind energy capacity of 45,000 MW, a figure well in line with the current planning of off-shore wind parks in Germany.

It would wrong to conclude, however, that the vision of a renewable hydrogen system will have to be abandoned. On the contrary, a first intermediate result is that the current expansion of RES needs to be pursued and accelerated. Special attention should be given to technologies with base load characteristics such as geothermal power (HDR) and the possibilities of importing RES electricity e.g. from solar thermal power plants in the south of Europe. At the same time, however, it becomes evident that only significant efficiency gains in all end-use sectors can reduce the demand for renewable energy to a realistic level. Taking these preconditions into account and applying a suitable long-term time frame, hydrogen is and will be an environmentally sound fuel option.

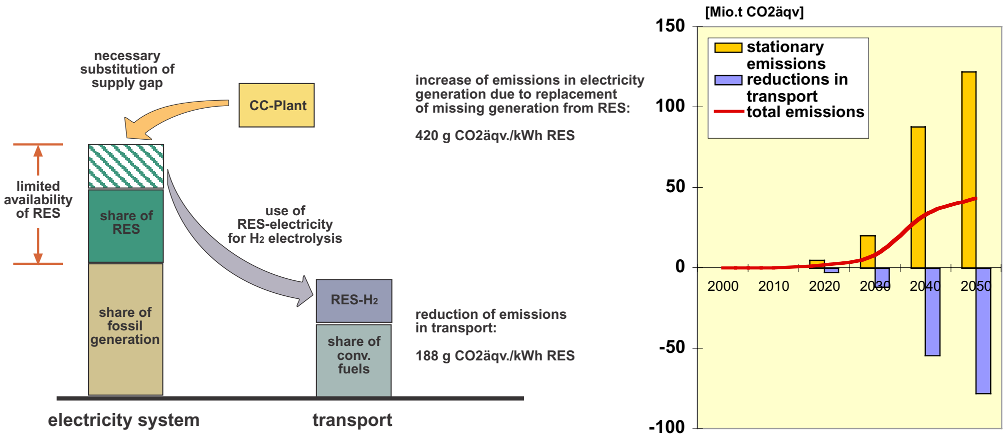
5.2 The input of renewable energies has to be optimised

In addition to the limits of capacity growth there is another short- to mid-term problem for RES input into hydrogen production: The various energy carriers can be used for different stationary and mobile applications (cf. chapter 4.3). From the system perspective, therefore, the input of RES with limited availability has to be optimised as far as possible, i.e. each energy carrier has to be used in the way that most benefits both the environment and the total energy system.

Consider the following example: Under current conditions, 1 kWh of RES electricity can substitute enough public-grid generation to prevent specific emissions of some 590 g CO_2eqv/kWh. If RES electricity is used in electrolysis and therefore, in the end, for hydrogen vehicles, a reduction of specific emissions by 191 g CO2eqv/kWh can be achieved. Direct use in the electricity system, in turn, yields a contribution to climate change abatement that is nearly three times higher than in the transport sector.

To put it the other way around, since the potentials for renewables are limited, any shift of RES electricity to the transport sector creates a need to maintain fossil power production or even build new capacities. This is a bad bargain for the environment, but the next decades are unlikely to bring a better one (Fig. 7). For these reasons, using RES for hydrogen electrolysis is by no means an emission-free option, but induces emissions from fossil power plants needed to meet the stable electricity demand of end users. In a holistic assessment of the energy system, the resulting specific emissions have to be assigned to hydrogen production from renewables.

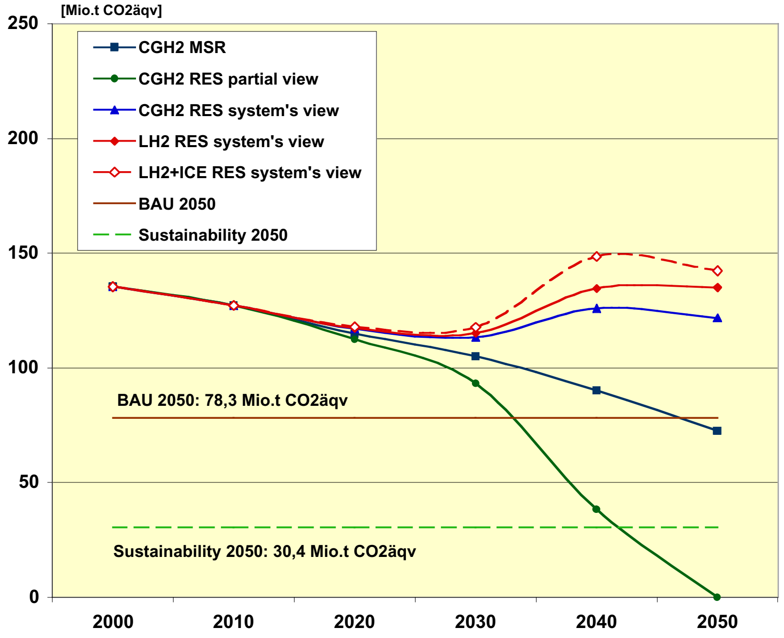
Fig. 7: Holistic assessment of the specific emissions of hydrogen production from renewables



5.3 Holistic assessment of the specific emissions of hydrogen production from renewables

The ecological impacts at the system level are illustrated in Fig. 8, taking the stretched introduction (100% hydrogen vehicles by 2050) as an example. The specific energy consumption of the vehicle fleet improves in accordance with the trend line.

Fig. 8: Holistic assessment of the specific emissions of hydrogen production – stretched introduction (100% by 2050)



If we consider the transport sector in isolation, it does look as though using RES electricity could cut specific GHG emissions down to zero (CGH_2 RES, isolated view). For the holistic assessment a best-case assumption was made, i.e. the resulting supply gap is covered by new, highly efficient combined-cycle power plants (spec. emissions of 421 g CO_2eqv/kWh). The overall emissions related to the CGH_2 supply jump to 118 million tons CO_2eqv in 2050 (CGH_2 RES, system view). This path even surpasses the BAU case, which relies heavily on fossil fuels, by 50%. With the present generation mix in Germany, specific emissions would be at approx. 590 g CO_2eqv/kWh, with worse results in the net balance.

Using RES electricity in hydrogen fuel generation is counter-productive from an ecological point of view as long as the specific emissions of the German electricity system are above 191 g CO2eqv/kWh. This level represents a share of RES in total power generation of more than 50%. Even the ambitious UBA sustainability scenario does not expect this situation to be achieved before 2040, and then only with the help of imported electricity from solar thermal power plants.

6 Impacts of the introduction of alternative fuels on the demand for natural gas

Natural gas offers several advantages when used as an alternative fuel. As mentioned, it enables to reduce local emissions and provides a limited but nonetheless worthy contribution to climate change abatement. Moreover, natural gas replaces the still dominating fuel oil and helps to diversify the energy supply in the transport sector. However, in order to take benefit from these positive effects the additional gas demand in transport should not induce new problems with regard to the security of supply of fossil fuels.

Direct use of natural gas in CNG vehicles induces a maximum demand of 129 PJ in 2020 (consistent with current trends and a 10% share). In subsequent years the gas demand is expected to decline as efficiency increases, reaching an assumed 89 PJ in 2050. When keeping the overall gas demand constant, this would imply to steadily increase the share of CNG vehicles from 10% in 2020 to 15% in 2050. In the case of high-savings, gas demand falls as low as 34 PJ.

Indirect use in methane steam reforming (MSR) for hydrogen production induces a maximum demand in the forced introduction case with full coverage of the hydrogen demand by MSR. Here the extreme is at 1,223 PJ in 2040. As we have seen, however, more realistic pathways rely on a moderate introduction and a generation mix with a declining share of MSR, in this case the demand will peak at 173 PJ in 2050.

Summing up, a combination of a moderate introduction with a 10% share of CNG vehicles yields a demand for natural gas of 240-270 PJ that remains stable after 2030 (Tab. 2).

Tab. 2: Development of demand for natural gas in the case of moderate introduction of hydrogen and a 10% share of CNG vehicles

Natural gas [in PJ] used for:	**2010**	**2020**	**2030**	**2040**	**2050**
- H_2 production	0	34	111	165	173
- CNG vehicles	30	129	119	105	89
total [in PJ]	**30**	**165**	**240**	**270**	**262**
total [in TWh]	*8.3*	*45.8*	*66.7*	*75*	*72.8*

Assumptions:
- Share of H_2 vehicles 50% in 2050, share of CNG vehicles 10% in 2020, then stable
- Development of average fleet consumption according to current trends
- H_2-generation by mix of MSR and growing share of RES up to 66% in 2050

Compared to the total gas demand in Germany, which reached 3,113 PJ (865 TWh) in 2002, the transport-related demand for private passenger cars corresponds to an additional 9%[25]. At the same time, it has to be taken into account that in many stationary applications demand is declining due to efficiency measures and substitution effects by a growing share of RES[26].

With regard to the security of supply, the introduction of natural gas as a new alternative fuel option in the transport sector with a share of 10% CNG vehicles and a limited hydrogen production presents no real problem. Independent of its mobile applications, more general risks arise from the growth dynamics in global gas markets and the resulting pressure on prices. Compared to other regions, however, Western Europe has a geographic advantage in its relative proximity to the gas sources. Moreover, good business relations between gas producers were established during the last decades, so that sufficient access to the remaining resources is guaranteed. Nonetheless, it has to be kept in mind that especially in the case of the Russian infrastructures, an enormous capital demand for maintenance and capacity enhancement will have to be met in the coming decades.

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[25] AGEB 2003

[26] Compared to other world regions, until 2030 the expected growth rate for the European gas demand will be rather low (0.8 %/a) (European Commission 2003b).

7 Summary and conclusions

- Research has shown that a substantial decrease in the average energy consumption of the vehicle fleet is a necessary condition if the long-term GHG reduction targets essential to combating climate change are to be met. Alternative fuels can complement the required energy saving measures and broaden the scope of action, but do not obviate the need for massive efficiency gains.
- Natural gas can play a role as an alternative fuel in transport, both when used directly for CNG vehicles and as a feedstock in a generation mix for hydrogen production. The particular advantages of natural gas are that it allows mitigating local emissions and at the same time diversifying the transport fuel supply in the short term.
- Specific GHG emissions of the natural gas fuel chain are up to 18% lower compared to the gasoline/diesel supply, depend on the supply structure. In order to take benefit from the fuel-related advantage, technical progress with regard to CNG engines has to be accelerated in order to approximate the diesel engine.
- There are different modes of using natural gas as a transport fuel. Using remote gas for the production of synthetic diesel (GTL) induces higher energy losses and GHG emissions than a direct use in LNG/CNG. From an environmental perspective, the GTL option tends to be counterproductive, and under current conditions, substantial technical or economic advantages of the exploitation of remote gas via GTL compared to LNG/CNG are not observable either. Advantages of GTL as a liquid fuel are still valid in areas where no sufficient CNG infrastructure exists.
- The GTL pathway does not offer generic advantages in a conversion of biomass to fuels because, as in the case of the Fischer-Tropsch synthesis, bio-methane can also be generated in a gasification process. However, in this field substantial demand for further R&D can be identified.
- Given that an efficient gasification process for producing bio-methane in large quantities becomes available, the estimated potential for biogas/bio-methane is significantly higher than the potential for liquid biofuels.
- Refining and up-grading biogas to feed into the natural-gas grid will augment market opportunities for biomass fermentation and gasification. Cost-effective and reliable technologies and a suitable access to the gas grid are the preconditions for an enhanced use of biogas in new applications such as transport.
- The ecological assessment of the various fuels paths yields the conclusion that for both natural gas and hydrogen, the compressed gas path entails lower conversion losses and GHG emissions than the liquefaction of gas. From the perspective of climate change abatement, compressed gas pathways appear to be preferable to liquid paths, so that the contribution that the CNG option can make to preparing future CGH_2 infrastructures needs to be explored in further detail.

Natural gas offers a lasting perspective as an alternative fuel that does not contradict the hydrogen option. On the contrary, during the coming years natural gas can take a bridging role for the preparation of a hydrogen system:

- A sustainable hydrogen economy can only be realised in the long term and on the basis of renewable energy sources (RES). In this context, nuclear energy is not a sustainable option for generating hydrogen. It comes with inherent technology risks, and the question of nuclear waste disposal remains unsolved. Moreover, few societies fully accept nuclear energy as a solution. The large-scale use of fossil fuels in combination with carbon sequestration, where manifold technical, economic and ecological aspects remain unclear, is a highly questionable option, too. Even putative technological breakthroughs cannot extend the future potential of carbon sequestration beyond the limits of the availability of suitable reservoirs.
- Any strategy to establish a renewable hydrogen system has to take into account the limits to accelerating the growth of RES capacity in Germany. Comparable obstacles hamper RES imports from foreign sources since the countries of origin also need to discuss the allocation of RES. And finally, building the necessary infrastructures for energy transport will simply need time.
- In theory, the RES potentials appear to be sufficient for covering the total energy demand of the passenger car sector before the year 2050. In reality, however, it will hardly be possible to access these capacities without violating other criteria of sustainable development.
- In terms of hydrogen production from RES electricity, a realistic and ecologically sound pathway can only be achieved if
    - the final energy demand for H_2 can be reduced through a substantial decrease of average fleet consumption (high savings), and
    - the new fuel option H_2 is introduced along a moderate introduction and the production is based on a generation mix that starts from MSR and slowly converts to the use of RES.
- Hydrogen pathways that incorporate relatively high conversion losses have to be seen critically. In the case of a development consistent with current trends, a 100% introduction of LH_2 for internal combustion engines will most likely fail to deliver a contribution to climate change abatement compared to the BAU case without alternative fuels.
- When considering the use of RES for mobile applications, one has to take into account that for the decades to come, higher emission reduction effects are likely to be achieved in the stationary sector. One example is the substitution of fossil power plants through RES electricity. From a holistic energy system perspective, the input of renewable energies into hydrogen electrolysis will induce an overall net increase of GHG emissions.
- As long as the total energy system relies largely on fossil fuels, substitution effects will eliminate any gains from RES-based hydrogen production for transport uses. A clean and abundant energy source for transport will not be available for quite some time.

- An accelerated introduction (100% coverage as early as 2035) does not provide any advantages for climate change mitigation. In effect, compared to the stretched introduction, a higher energy and hydrogen demand would result. From a climate policy point of view, there is no need for an accelerated introduction of the hydrogen ICE as an end-use application.

The introduction of hydrogen before the year 2050 does not promise any substantial contribution to mitigating GHG emissions, nor is it necessary from the holistic energy systems perspective if the two **key strategies, energy efficiency and growth of renewable energies**, are vigorously pushed ahead in all energy sectors. This means both squeezing the energy demand of the vehicle fleet as well as realising the energy efficiency potential in stationary applications, which would relieve some of the demand pressure on scarce RES supplies. The alternative fuel option natural gas (CNG) represents a sensible complement to this dual strategy while preparing the ground for a future hydrogen system. Once RES are available in large quantities and form a major part of the energy supply, a situation targeted for 2050, hydrogen can play its role in supporting RES up to the ultimate goal of a practically GHG-free energy system. Summing up, different phases of increasing the share of RES and introducing alternative fuels can be distinguished in the transition to a hydrogen system:

- **Until 2010** **Entry phase** into short-term alternative fuels and acceleration of RES growth backed by energy policy through target setting and support policies
- **2010-2020** **Stabilisation** of RES growth and gradual withdrawal of policy support, consolidation of the contribution of CNG and biofuels
- **2020 - 2035** Full **consolidation** of new RES technologies in all end-use sectors and start of trans-European exchange of RES energy, first application of hydrogen in distinctive niches while maintaining the established alternative fuels
- **2035 - 2050** **Growing dominance** of RES in all end-use sectors and start of significant use of hydrogen
- **Beyond 2050** **Gradual substitution of fossil energy** by RES and large-scale establishment of hydrogen from RES in order to realise a rhydrogen system by the end of the 21st centuryThe present study discussed the energy- and climate policy aspects of an introduction of alternative fuels in the sector of private passenger cars. To provide a comprehensive analysis of the whole transport sector, a next step should focus on the areas of freight and public transport, which are characterised by specific conditions and market mechanisms. The basic conclusions, however, are not likely to change substantially. In fact, they will probably underpin what we have seen with the already scarce RES reservoir and the related allocation effects: Additional demand will certainly increase competition. Moreover, the present focus on ecological criteria needs to be complemented by economic analyses of costs and business perspectives.

Furthermore, the scope of analysis has to be enlarged to the European dimension. In this context, regional aspects and differences between member states will gain importance. Special research questions arise in terms of an optimised allocation of the biomass potential. As we have seen, a holistic and dynamic assessment that counts for interdependencies in terms of a systems analysis has yet to be compiled and requires far more research.

In this context, open questions still remain with regard to the technological aspects of natural gas as a bridging technology, both in relation to an enhanced use of bio-methane as well as to the establishment of a hydrogen infrastructure. A more profound analysis of transition processes and the related time frame, the key technologies and synergy potentials promises to provide a better understanding of the feasibility, but also the probable costs, of the intended change of systems.

8 Glossary

BCMG	biogeneous compressed methane
BTL	Biomass-to-Liquid (synthetic diesel from biomass)
CC	combined cycle power plant
CGH_2	compressed hydrogen
CH_4	methane (natural gas)
CMG	compressed methane
CNG	compressed natural gas
CO_2äqv	CO_2 greenhouse gas equivalent
FTD	Fischer-Tropsch-Diesel (synthetic diesel)
GTL	Gas-to-Liquid (synthetic diesel from natural gas)
LH_2	liquefied hydrogen
LNG	liquefied natural gas
MSR	methane steam reforming
NO_x	nitrous oxids
RES	renewable energy sources
RME	Rapsmethylester (biodiesel)
GHG	greenhouse gas
UBA	Umweltbundesamt
VOC	volatile organic compounds
TWh	Terawatthours = 10^{12} Wh (1 billion kWh)
MJ	Mega Joule = 10^{6} J
PJ	Peta Joule = 10^{15} J

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10 Appendix

10.1 General procedure

The following description briefly outlines the general procedure for the calculations, analyses and interpretations made in the main part.

- The motorised individual transport sector (MIV) has been chosen as matter of investigation, because there are far more choices for different alternative fuels and power train technologies than in any other transport sector and it is of big importance both in a political as well as in an ecological sense.
- Starting point for the model calculations are the current long-term scenarios for the German ministry of environment (UBA), i.e. the reference (REF) and the sustainability (NH) case (Fischedick, Nitsch et al. 2002). A new calculation model for the MIV has been build up by separating the corresponding MIV-sector from the UBA-scenarios, added by some modifications and supplements in order to obtain a sound model regarding the ecological and energy related effects of alternative fuel introduction. As a basic assumption, a common development of transport demand has used according to the UBA-REF case, excluding any consumer behaviour related traffic reductions. As point of departure, a base case relying on a mix of conventional fuels (2/3 gasoline and 1/3 diesel) without any alternative fuel has been defined. Against this background the impact of the selected fuel paths was studied by increasing the share of the specific fuel option while decreasing the share of conventional fuels homogeneously to the debit of gasoline and diesel (see page 2). Compared to the UBA scenario, additional fuel options (FTD and BCMG) and their characteristics as well as car types (natural gas diesel motor) have been integrated within the new model cases.
- For each fuel path the ecological and energetic development of the MIV-sector (CO_2-emissions and final energy demand) has been calculated by use of five parameters (see Fig. 1). The total car stock in the year 2000 has been linearly extrapolated until 2050 in correspondence to the development of the transport demand[1] and the average car passenger number. With respect to the average yearly driving distance however it has been assumed that it will remain constant over the time horizon (i.e. unchanged mobility behaviour). Fuel shares have been fixed solely for each fuel path. The specific fuel consumption follows the outline of two new development lines TREND and HIGH-SAVINGS (cf. chapter 3). Concerning FTD and natural gas power trains it has been assumed that they will benefit from future progress and therefore approximate conventional power train technologies. The fuel path emission factors (see page 3) are taken from the GM “Well-to-Wheel“ Study (LBST 2002a).
- The analysed time horizon covers the decades between the year 2000 and 2050.
- If electricity from renewables will be used for H_2-production, the results for the corresponding CO_2-emissions also consider allocation effects between stationary and mobile applications (cf. chapter 4.3 and chapter 5.3)

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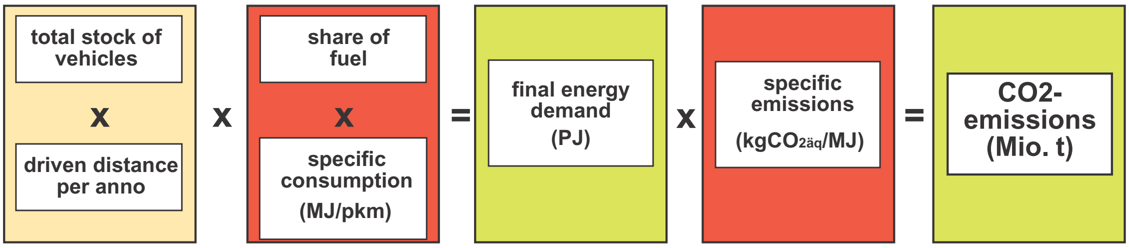
[1] Mainly triggered by the development of population.

Fig. 1: Algorithm for final energy consumption and CO_2-Emissions within the MIV-sector



10.2 General Assumptions

Parameter	Unit	Year					
		2000	2010	2020	2030	2040	2050
traffic intensity MIV$^{1)}$	Bil. Pkm	744,3	864,4	899,2	897,1	856,8	783,7
car passenger number$^{1)}$	Persons	1,41	1,42	1,44	1,44	1,44	1,44
car stock$^{2,3)}$	Mil. car	42,4	48,9	50,2	50,1	47,8	43,7
car driving distance$^{3)}$	km/a	12.442					
CO_2-Emission factors$^{4)}$	CO_2-äq./MJ	see separate table (Appendix page 3)					
Conversion efficiencies							
* Steam Reforming$^{)}$	%	66,3	68,5	70,0	70,0	70,0	70,0
* Electrolysís$^{1)}$	%	73,8	76,0	77,0	80,0	80,0	80,0
* H2-Licquefaction$^{4)}$	%	72,4	74,7	77,1	77,1	77,1	77,1
* H2-Compression up to 80 Mpa$^{5,*)}$	%	81,4	81,4	82,2	83,0	83,9	84,7
REG-electrolyse-Share, MIX-path	%	0	0	5	20	40	65
MSR-Share, MIX-path	%	100	100	95	80	60	35
Full load hours wind power	h/a	2.000					

$^{*)}$ value for CGH2-refueling station; cf. various ranges for compressor efficiencies by sources: 61,6-73,6% (LBST 2002a); 78-83% (Shell 2001); about 88,5% (Bossel/Eliasson)

Sources: $^{1)}$ Fischedick, Nitsch et al. 2002; $^{2)}$ Statistisches Bundesamt 2002; $^{3)}$ own calculations; $^{4)}$ HYWEB2002; $^{5)}$ LBST 2002a,

10.3 Introduction pathways under consideration for selected alternative fuel cars

	2000	**2010**	**2020**	**2030**	**2040**	**2050**
Total car stock [Mil. car]	42,4	48,9	50,2	50,1	47,8	43,7
Stock share H2-cars						
* forced introduction	0%	0%	20%	82%	100%	100%
* stretched introduction	0%	0%	2%	12%	59%	100%
* moderate introduction	0%	0%	2%	10%	22%	49%
CNG/BCMG/FTD-car stock share	0%	2%	10%	10%	10%	10%
* CNG-Max	0%	2%	10%	40%	75%	100%

Source: Fischedick, Nitsch et al. 2002; own calculations

10.4 Selected emission factors of alternative fuels

Specific GHG-emissions	Fuel chain	Vehicle emissions1)	Local CH_4 and N_20 emissions2)	**Total**
	[in g CO_2eqv/MJ]			
Petrol	13.2	73.4	2.4	89.0
Diesel	10.4	72.8	1.7	84.9
FT-diesel (remote gas)	28.0	71.0	0.0	99.0
Biodiesel/RME3)	-48.0	76.7		28.7
FT-Diesel (biomass)	-62,0	71,0		9,0
CNG 250bar4)	14.0	56.4	2.4	72.8
CNG (via LNG)	16.0	56.4	2.4	74.8
CMG 250bar (fermentation)	-56.7	56.9		0.2
CGH_2 700bar (EU gas, dec. MSR)	103.0	0.0		103.0
CGH_2 700bar (waste wood gasification)	7.0	0.0		7.0
CGH_2 700bar (Wind power, decentral. electrolysis)	0.0	0.0		0.0
LH_2 (MSR)	124.0	0.0		124.0
LH_2 (Wind power, central electrolysis)	2.0	0.0		2.0

Source: LBST 2002a
Negative values count for carbon content of biomass input.
Renewable energy paths are seen from the transport sector and do not reflect systemic effects.
1) CO_2 content of fuel
2) conventional drive trains
3) best estimate for RME (11.5 – 77.9 g CO_2eqv/MJ)
4) supply from EU mix

10.5 Exemplary calculation of the gross efficiency of REG-Electricity when used for H_2-electrolysis

Path: BAU_moderat_CGH2_MIX	**Unit**	**2000**	**2010**	**2020**	**2030**	**2040**	**2050**
Net CO_2 Emissions	Mil. t CO_2-Äqv.	135,5	127,3	114,9	103,1	84,0	52,4
H_2 final energy demand	PJ	0,0	0,0	24,8	97,6	192,2	345,9
Electrical Efficiency of electrolyse	%	73,8	76,0	77,0	80,0	80,0	80,0
Electrical Efficiency of Compression (to 80 MPa)	%	81,4	81,4	82,2	83,0	83,9	84,7
Share of electrolyse, MIX-path	%	0,0	0,0	0,1	0,2	0,4	0,7
Electricity demand	TWh	0,0	0,0	0,5	8,0	30,2	88,2
Emission factor CC-Plant	kg CO_2 äqv./kWh	0,4	0,4	0,4	0,4	0,4	0,4
For comparison public Electricity-Mix	kg CO_2/kWh	0,6	0,6	0,5	0,5	0,5	0,5
Induced CO_2-Emissions	Mil. t CO_2-Äqv.	0,0	0,0	0,2	3,4	13,4	38,8
Gross CO_2-Emissions	Mil. t CO_2-Äqv.	135,5	127,3	115,1	106,5	97,4	91,2

10.6 Specific fuel consumption patterns of selected power trains

Trend (BAU)	2000	2010	2020	2030	2040	2050	2000 - 2050
	[MJ/Pkm]						[%]
Gasoline	2,10	1,74	1,50	1,37	1,26	1,16	-45
Diesel	1,92	1,53	1,38	1,28	1,19	1,10	-43
FTD (fossil)	1,92	1,53	1,38	1,28	1,19	1,10	-43
Bio Diesel (RME)	2,00	1,53	1,38	1,28	1,19	1,10	-45
FTD (biogen)	2,00	1,53	1,38	1,28	1,19	1,10	-45
Natural Gas OM	2,16	1,74	1,50	1,37	1,26	1,16	-46
Natural Gas DM	2,16	1,53	1,38	1,28	1,19	1,10	-49
Hydrogen OM	2,10	1,56	1,35	1,23	1,15	0,95	-55
Hydrogen BZ	2,10	1,25	1,20	1,10	1,00	0,90	-57

High-Saving (HS)	2000	2010	2020	2030	2040	2050	2000 - 2050
	[MJ/Pkm]						[%]
Gasoline	2,10	1,67	1,33	1,05	0,86	0,45	-79
Diesel	1,92	1,59	1,25	1,00	0,81	0,43	-78
FT-Diesel (fossil)	1,92	1,59	1,25	1,00	0,81	0,43	-78
Bio Diesel (RME)	2,00	1,59	1,25	1,00	0,81	0,43	-79
FT-Diesel (biogen)	2,00	1,59	1,25	1,00	0,81	0,43	-79
Natural Gas OM	2,16	1,67	1,33	1,05	0,86	0,45	-79
Natural Gas DM	2,16	1,59	1,25	1,00	0,81	0,43	-80
Hydrogen OM	2,10	1,51	1,19	0,94	0,63	0,41	-80
Hydrogen BZ	2,10	1,25	1,05	0,90	0,60	0,39	-81

OM: gasoline motor; DM: diesel motor; BZ: fuel cell

Sources: Fischedick, Nitsch et al. 2002, own calculations

10.7 CO$_2$-Emissions of analysed fuel paths (in Mil. t CO$_2$-Äqv.)

Fuel path	2000	2010	2020	2030	2040	2050	2000-2050 cumulative
BAU (basis path)	135,5	127,3	115,1	105,4	92,9	78,3	5.584
BAU_forced_CGH2_MSR	135,5	127,3	114,4	102,3	88,2	72,6	5.466
BAU_forced_LH2_REG	135,5	127,3	92,9	20,2	1,7	1,4	3.173
BAU_forced_LH2_REG_brutto	135,5	127,3	134,8	174,3	164,0	135,1	7.492
BAU_forced_LH2_ICE_REG	135,5	127,3	92,9	20,4	2,0	1,5	3.179
BAU_forced_LH2_ICE_REG_brutto	135,5	127,3	140,1	193,1	187,9	142,5	8.012
BAU_stretched_CGH2_MSR	135,5	127,3	115,0	105,1	90,1	72,6	5.519
BAU_stretched_CGH2_REG	135,5	127,3	112,4	93,3	38,4	0,0	4.459
BAU_stretched_CGH2_REG_brutto	135,5	127,3	117,0	113,4	126,0	121,8	6.251
BAU_stretched_LH2_REG	135,5	127,3	112,5	93,6	39,4	1,4	4.480
BAU_stretched_LH2_REG_brutto	135,5	127,3	117,3	115,1	134,6	135,1	6.432
BAU_stretched_LH2_ICE_REG	135,5	127,3	112,5	93,6	39,5	1,5	4.482

Fuel path	2000	2010	2020	2030	2040	2050	2000-2050 cumulative
BAU_stretched_LH2_ICE_REG_brutto	135,5	127,3	118,0	117,8	148,6	142,5	6.645
BAU_moderate_CGH2_MSR	135,5	127,3	115,0	105,1	91,9	75,6	5.553
BAU_moderate_CGH2_MIX	135,5	127,3	114,9	103,1	84,0	52,4	5.325
BAU_moderate_CGH2_MIX_brutto	135,5	127,3	115,1	106,5	97,4	91,2	5.709
BAU_CNG	135,5	127,0	113,1	103,6	91,3	77,0	5.517
BAU_CNG_MAX	135,5	127,0	113,1	97,9	80,5	64,5	5.284
BAU_GTL	135,5	127,4	115,9	106,3	93,7	79,1	5.613
BAU_BIOCMG	135,5	124,8	103,7	94,9	83,7	70,5	5.204
HS (basis path)	135,5	125,3	102,6	81,2	63,5	30,4	4.638
HS_CNG	135,5	124,9	100,8	79,8	62,4	29,8	4.588
HS_moderate_CGH2_REG	135,5	125,3	100,2	73,2	49,2	15,5	4.310
HS_moderate_CGH2_REG_brutto	135,5	125,3	104,2	87,3	69,3	41,4	5.914

10.8 Final Energy demand of analysed fuel paths (in PJ)

Fuel path	2000	2010	2020	2030	2040	2050	2000-2050 cumulative
BAU (basis path)	1.534	1.448	1.313	1.202	1.060	894	63.580
HS (basis path)	1.534	1.427	1.170	927	724	346	52.816
H_2 demand							
BAU_forced_CGH2_MSR	0	0	213	813	856	705	22.702
BAU_forced_LH2_REG	0	0	213	813	856	705	22.702
BAU_forced_LH2_ICE_REG	0	0	239	911	981	744	25.408
BAU_stretched_CGH2_MSR	0	0	25	114	503	705	10.291
BAU_stretched_CGH2_REG	0	0	25	114	503	705	10.291
BAU_stretched_LH2_REG	0	0	25	114	503	705	10.291
BAU_stretched_LH2_ICE_REG	0	0	28	128	576	744	11.403
BAU_moderate_CGH2_MSR	0	0	25	98	192	346	5.048
BAU_moderate_CGH2_MIX	0	0	25	98	192	346	5.048
HS_moderate_CGH2_REG	0	0	22	80	115	150	2.993
Gas demand							
BAU_CNG	0	30	129	119	105	89	4.319
BAU_CNG_MAX	0	30	129	475	787	886	19.090
BAU_GTL	0	26	124	115	102	86	4.145
BAU_BIOCMG	0	30	129	119	105	89	4.319
HS_CNG	0	30	129	119	105	89	4.319