THE POTENTIAL OF NATURAL GAS AS A BRIDGING TECHNOLOGY IN LOW-EMISSION ROAD TRANSPORTATION IN GERMANY

by

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Greenhouse gas emission reductions are at the centre of national and international efforts to mitigate climate change. In road transportation, many politically incentivised measures focus on increasing the energy efficiency of established technologies, or promoting electric or hybrid vehicles. The abatement potential of the former approach is limited, electric mobility technologies are not yet market-ready. In a case study for Germany, this paper focuses on natural gas powered vehicles as a bridging technology in road transportation. Scenario analyses with a low level of aggregation show that natural gas-based road transportation in Germany can accumulate up to 464 million tonnes of CO_2*-equivalent emission reductions until 2030 depending on the speed of the diffusion process. If similar policies were adopted EU-wide, the emission reduction potential could reach a maximum of about 2.5 billion tonnes of* CO_2*-equivalent. Efforts to promote natural gas as a bridging technology may therefore contribute to significant emissions reductions.*

Key words: *emission reduction potential, natural gas vehicles, alternative fuels, road transportation*

Introduction

To mitigate climate change, Germany aims at the reduction of greenhouse gas (GHG) emissions. Although there are tax-incentives and regulations aiming to reduce the specific emissions of cars, road transportation is still largely based on high carbon petroleum fuels and accounts for nearly one fifth of GHG emissions in Germany. Though new technologies like electric and fuel cell vehicles get a lot of publicity as well as research and development subsidies (R&D) they are still far away from being market-ready.

This paper explores the potential of natural gas as a bridging technology in road transportation in a case study for Germany. This alternative fuel is available in large quantities; its technology is marketable and already applied on a large scale in several countries. Specific investment costs are only slightly higher than those for conventionally fuelled vehicles. GHG emissions from natural gas-based road transportation are significantly

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lower than those of petroleum-based mobility. As a fossil fuel, however, the potential of natural gas to reduce emissions is limited. Nevertheless, it may contribute to lowering road transportation emissions in the next years until new, low-emission technologies are ready for the market.

By means of a scenario analysis, the present paper focuses on the quantification of the emission reduction potential of an intensified use of natural gas in road transportation and determines the requirements for and consequences of its realization.

Therefore, the next section presents the prospects of natural gas mobility by investigating the experiences from other countries and the findings given by literature. Subsequently, we outline the barriers currently preventing a transformation of the transport sector from petroleum- to natural gas-based mobility and provide an indication of what would be necessary to overcome these obstacles. We design a scenario of maximum natural gas vehicle (NGV) diffusion in road transportation assuming that all existing barriers were removed. This enables an estimation of the emission savings potential.

Transport emissions, options for emission reductions and natural gas in road transportation

The transport sector accounts for a significant part of global GHG emissions. In Germany, 153 megatonnes (Mt) CO_2-equivalent (eq.) – 17% of the total 920 Mt CO_2-eq. generated in Germany – fell upon the transport sector in 2009. With 146 Mt CO_2-eq., 95% of all transport sector emissions accrued in road transportation [1]. This makes road transportation a key sector for efforts to reduce emissions. For this purpose several options are available:

- the reduction of transport activity
- shifting traffic to more sustainable modes of transport, and
- the reduction of emissions per vehicle kilometre (km) [2].

The latter could be achieved, for instance, by improving traffic flow or driver behaviour as well as with technological vehicle improvements or the use of lower emitting fuels. The use of biofuels, electric mobility and fuel cell vehicles may result in lower emissions than petrol and diesel. As the following section shows, natural gas is also an alternative fuel allowing for emission reductions.

The climate balance of different fuel and powertrain options is compared based on a well-to-wheel (WTW) analysis [3]. This analysis comprises the emission of the total value chain of a fuel or powertrain option, *i. e.* the sum of all emissions that result from the provision of the particular primary energy (well-to-tank, WTT) and those accumulating when using the propulsion means in the vehicle (tank-to-wheel, TTW). While TTW emissions solely depend on the respective energy source, WTT emissions differ depending on the fuel chain and mode and distance of transport of the energy source. Thus, WTT emissions of natural gas which has been transported by pipeline over a distance of 7,000 km (*e. g.* from Western Siberia) are more than twice as high as those of natural gas in the current EU-mix (21.69 *vs*. 8.52 g CO_2-eq./MJ). Natural gas from regions like South-West Asia (4,000 km via pipeline) lie between these values with WTT emissions of 14.02 g CO_2-eq./MJ.

Nevertheless, all three of these natural gas supply options reduce total emissions per unit of energy compared to petrol and diesel: with WTW emissions of between 66.50 and 79.67 g CO_2-eq./MJ depending on the fuel chain and referring to the energy used in the vehicle, natural gas generates 11 to 25% less emissions per unit of energy than diesel. The emission reduction per energy unit compared to petrol is somewhat smaller (tab. 1).

Table 1. Specific CO_2-eq. emission factors of fuel and powertrain options (in g CO_2-eq./ MJ) [arithmetic average of values in 3, 4, and 5]

	Well-to-Tank	Tank-to-Wheel	Well-to-Wheel
Petrol	12.47	74.30	86.77
Petrol substitute from biomass	–31.51	72.19	40.68
Diesel	14.18	74.50	88.67
Diesel substitute from biomass	–34.65	77.40	42.75
Natural gas EU-mix 2010	8.52	57.98	66.50
Natural gas pipeline 4,000 km	14.02	57.98	72.01
Natural gas pipeline 7,000 km	21.69	57.98	79.67
Biogas	–55.20	57.98	2.78
LPG (liquefied petroleum gas)	7.97	66.19	74.16
Electric powertrain	163.48	0.00	159.72

In addition to emission reductions of GHG, the use of natural gas in road transportation also produces less air pollutants than the use of diesel and petrol. Passenger cars fuelled with natural gas emit 80% less reactive hydrocarbons than those fuelled with diesel (compared to passenger cars fuelled with petrol: –80%), 80% less nitrogen oxides (NO_x; –20%), 50% less carbon monoxide (CO; –75%), up to 99% less sulphur dioxide, carbon black and particulate emissions and up to 50% less noise emissions. Furthermore, natural gas contains significantly less toxic components such as BTX and aldehydes and does not cause evaporation loss or odour nuisance during refuelling [6].

The mentioned advantages are some of the reasons why the global use of natural gas in road transportation has increased significantly since the early 1990s and especially since the turn of the millennium. At the end of 2009, 11.3 million (M) NGV were in use – nearly nine times as many as in 2000 [7]. While NGV growth rates are especially high in Asia and Latin America, rises in the usage of NGV in Europe have so far been moderate. In 2009, 1.3 M NGV operated in Europe. Globally, Pakistan currently has the largest NGV fleet with a total of 2.3 M NGV and more than 3,000 natural gas stations. Between 1.6 and 1.8 M NGV are in use in Argentina, Iran and Brazil while Italy has the largest number of NGV in Europe (nearly 629,000 NGV) [7].

At the end of 2009, out of the 46 M vehicles registered in Germany, about 85,000 were powered by natural gas. 80% of these vehicles are passenger cars and 20% utility vehicles including 1,800 heavy-duty vehicles and buses. With 0.146 Mt of oil equivalent (Mtoe), natural gas covered 0.3% of the total fuel consumption in Germany in 2009 [8].

Despite of the aforementioned characteristics of natural gas, most scenarios considering the transport sector do not assume natural gas to contribute significantly to the future fuel mix in Germany and the European Union (EU). Assumptions on the share of natural gas from a number of studies which regard the fuel mix in the transport sector or road transportation in Germany and the EU are presented in tab. 2.

To investigate why the diffusion of a new fuel in road transportation is difficult, the next section considers the process of the diffusion of a new technology as well as diffusion barriers. Furthermore, potential measures to overcome these barriers and enable establishing natural gas as a transport fuel are discussed.

Table 2. Share of natural gas in the transport sector and road transportation in considered scenarios for Germany and the EU 2020 and 2030 (in %)

	2020	2030
Transport sector Germany		
Energy scenarios prognos/ EWI/ GWS (2010) [9]	4.0%	7.2%
UBA-long term scenarios (2002) [10]	2.5%	5.2%
UBA-policy scenarios (2008) [11]	0-2.2%	0-3.7%
Energy economic master plan BDEW (2008) [12]	1.47-1.67	3.10-3.49
Primes NTUA (2006) [13, 14]	0.05-0.07%	0.07-0.08%
Transport sector EU		
World energy outlook 2009 IEA [15]	–	0.4%
Primes NTUA (2006) [13, 14]	0.12-0.19%	0.13-0.17%
Road transportation Germany		
Fuel matrix German government (2004) [16]	2-4%	–
Model Germany *Prognos*/Oeko-Institut (2009) [17]	1.24-1.4%	1.91-3.19%
Passenger cars EU		
EU energy trends to 2030 European Commission (2010) [18]	0.6%	0.6%

The diffusion of a new transport technology

The term "diffusion" describes the spread of a material or immaterial object within a system. In this part of the innovation process, a market-ready invention (innovation) is first adopted by users. The literature distinguishes innovations with respect to their novelty (incremental vs. radical) and their compatibility with existing systems (modular vs. system innovations) [19-22].

The transformation of road transportation from petroleum to natural gas requires more than only engine adaptations, mainly regarding petrol stations and the distribution and storage of the fuel (in vehicles and filling stations). The changes, however, are not radical because natural gas engines are only slightly different from gasoline engines, natural gas-petrol stations do not fundamentally differ from conventional ones, and natural gas distribution and storage are well-proven technologies. Hence, the described transformation process is an incremental system innovation. As the adoption of incremental innovations is usually not associated with large obstacles, the main barriers to a transformation process stem from its systemic nature [22].

A further characteristic of the diffusion of fuel and powertrain options in road transportation is the substitution of an existing technology. Hence, the maximum market potential of NGV – which is of great interest for the purpose of this work – equals the size of the market for road vehicles [21].

A typically s-shaped curve for a diffusion process over time is depicted

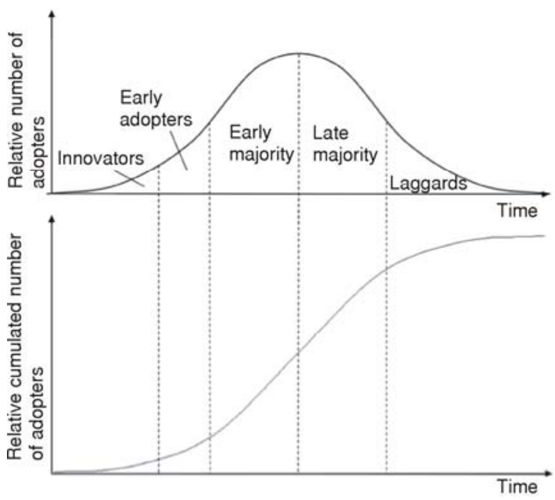

Figure 1. Typical adoption and diffusion curve [19, 21]

in fig.1. It illustrates that, generally, the diffusion of a technology starts rather slow (when so called innovators and early adopters adopt the technology, see fig. 1), accelerates until it peaks at an inflexion point and then declines steadily until the technology's market potential is reached [21].

In 2009, only 0.3% of the total fuel consumption in Germany was covered by natural gas [8]. This implies that natural gas based mobility is in the innovation phase of the diffusion process where only very few vehicle drivers have opted for the technology. Only limited potential for NGV diffusion is expected to result from converting the current rolling stock into NGV [23]. In case conversion is neglected, the maximum rate of diffusion of NGV possible equals the natural replacement rate of the rolling stock.

After a critical mass of adopters has opted for an innovation, its adoption is self-sustaining and the rate of diffusion takes off, stabilises and becomes irreversible (lock-in effect). If critical mass is not reached, over time the number of adopters decreases again [20]. For NGV, critical mass is not yet reached in Germany. Therefore, the following part of this section discusses and quantifies the barriers regarding an increased adoption of NGV in Germany and outlines what would be required to remove them.

Diffusion barriers

Road transportation in Germany is currently geared to fit the needs of petrol and diesel based mobility. The main barriers for the diffusion of NGV are associated to the filling station infrastructure, vehicle characteristics and capital and operating costs.

Filling station infrastructure

NGV are not compatible with conventional petrol stations. A well developed infrastructure for fuelling a vehicle, however, is a critical requirement for NGV adoption. Currently, the availability of facilities for fuelling NGV is insufficient to be comfortable for consumers. A level which would be sufficiently comfortable for consumers is expected to be at between 10 and 20% of currently existing conventional petrol stations [24, 25]. Above this threshold, the filling station infrastructure is no longer a barrier to NGV adoption for most customers and diffusion takes off; only a small number of potential customers requires a filling station infrastructure nearly equivalent to the one available for the fuelling of conventional fuels before the diffusion barrier disappears [26]. Below this threshold, the lack of filling stations is a crucial barrier for NGV diffusion. In Germany, about 860 of a total of 14,500 filling stations (a share of only about 6%) offered natural gas by the end of 2009 [7]. Hence, the number of natural gas filling stations should at least double in order to increase the comfort of potential adopters significantly.

The key determinant for filling stations to offer natural gas is profitability. Different studies assume that filling stations can offer natural gas profitably if there are at least 200 [8] or at least between 400 and 800 [27] NGV per filling station. Estimates vary because of different assumptions regarding margins and fixed costs, among other reasons [28]. Countries which have established considerable use of natural gas in road transportation have a ratio of about 1:1,000. Where diffusion was not successful, the ratio remained below 1:200 [24]. While the total filling station-to-vehicle ratio for all fuel and powertrain options in Germany is 1:3,200, there are 860 natural gas filling stations and 85,000 NGV. With a ratio of 1 to 99, it is not profitable for additional stations to offer natural gas because there is too little demand.

This demonstrates the difficulties of a systemic innovation such as NGV's: Consumers do not adopt the technology because there are too few filling stations. Simultaneously, additional stations do not open because there are too few consumers. Removing these systemic obstacles is therefore crucial for a successful diffusion of NGV.

The structural prerequisites for an expansion of the natural gas filling station infrastructure are favourable in Germany: The country has an extensive natural gas grid with a total length of about 400,000 km [8]. The maximum distance between two medium or high pressure gas pipelines is 40 km [29] implying that even remote locations are never further away from an access to the natural gas grid than 20 km.

Vehicle characteristics

Further obstacles to the diffusion of NGV are a consequence of the properties of NGV and of consumers' judgements with respect to their relative advantage.

The greatest advantage of NGV compared to conventionally fuelled vehicles is their more favourable emission and environmental balance. However, the positive outcome of NGV adoption for the global climate is an external effect and may therefore only be relevant for ecologically sensitive consumers.

As NGV are an incremental innovation which can be observed and tried easily and is proven [30], potential barriers to adoption resulting from the technology are low. In addition, the innovation is not complex and easy to understand by potential consumers, which generally has a positive impact on adoption [31].

However, natural gas as a fuel in road transportation also has properties which reduce the relative advantage of NGV. Even compressed natural gas (CNG) has a lower energy density than petroleum. Hence, to achieve a cruising range comparable to that of conventional cars, larger tanks have to be installed. Additionally, storing CNG requires heavier tanks than petroleum does [32, 33]. These characteristics reduce NGV efficiency and either cruising range (smaller amount of fuel) or loading space in the vehicle (larger tank). As most existing NGV models which cannot be switched to petrol sacrifice cruising range in favour of better loading space, NGV cruising range is usually only between 180 and 450 km [6, 34]. This characteristic may deter consumers from adopting the technology.

Additionally, only a limited amount of NGV models is currently available [8]. This may particularly deter consumers with brand or model loyalty from buying a NGV and confirms the problem of a systemic innovation: Car producers only offer a limited supply due to small demand, but demand does not increase because choice is limited.

Capital and operating costs

Capital and operation costs are a further crucial determinant for the adoption of NGV. On the one hand, NGV are usually more expensive with respect to initial investment costs. On the other hand, fuel prices for natural gas are well below those of petrol and diesel. A potential barrier for the diffusion of NGV may thereby result from a biased perception of future savings compared to start-up cost. A high implicit discount rate of future savings or low disposable income may deter potential users from adopting NGV.

Currently, investment costs for NGV exceed those for petrol and diesel vehicles by about 1,500 to 4,000 EUR for passenger cars and by up to 22,000 EUR for trucks and medium- and heavy-duty vehicles [8, 35, 36]. With higher market penetration, investment costs are expected to decline in the future due to learning curves and economies of scale [38]. Increasing emission standards also lead to rising costs for conventionally, especially diesel fuelled cars and improve the relative advantage of NGV [8]. Therefore, the additional capital costs of NGV are expected to decline to between 150 and 1,200 EUR by 2020 depending on the market penetration of NGV [38]. Nevertheless, the currently higher investment costs are an obstacle to diffusion.

Operating costs include technology-specific maintenance costs, fuel costs and taxes. The latter partially reflect the favourable emission balance of NGV compared to petrol and diesel vehicles: Until the end of 2018, taxes for natural gas as a fuel in Germany are about 80% lower than those for diesel and about 65% lower than those for premium petrol [8]. This contributes to significant fuel cost advantages for NGV which amount to up to 50% compared to petrol and up to 30% compared to diesel vehicles depending on vehicle km travelled [8]. Many consumers, however, do not perceive this advantage. Beside the lack of natural gas availability at most filling stations, fuel prices at filling stations are usually labelled in different units complicating an easy comparison of prices. Unified labelling, for instance in the same energy unit instead of litre (l) *vs*. kilogramme (kg), could help overcome this problem* [8]. Because of the tax advantage and lower commodity costs of natural gas, total operating costs are significantly lower for NGV than for conventionally fuelled vehicles. Maintenance costs are only slightly higher for NGV [36].

Therefore, the amortisation of the higher capital costs generally takes two to eight years for most passenger cars depending on vehicle km travelled each year as well as current energy and vehicle prices [8]. While this may be a sufficient argument for commercial vehicle purchases, private consumers usually demand a high discount factor when purchasing new technologies and an amortisation period of a maximum of three years for investments in reduced fuel costs [24]. Hence, most customers underestimate the actual cost effectiveness of NGV. The combination of high capital costs and the biased perception of the actual cost effectiveness of NGV poses another crucial barrier to diffusion of the technology in road transportation.

Removing the barriers for NGV diffusion

Measures to promote NGV need to address the described barriers hampering the diffusion of NGV. Due to systemic interconnections between various barriers, their removal is challenging: A one-sided increase in the number of natural gas stations removes the disadvantage of NGV resulting from the currently insufficient filling station infrastructure. However, it does not change the relatively high upfront investment costs of NGV, which was identified as another barrier to diffusion. Likewise, lowering investment costs does not necessarily mean potential adopters are satisfied with the variety of vehicle models offered.

Measures to promote NGV may be taken by all relevant stakeholders; a co-ordinated approach including various measures would increase the chances for success [21]. As NGV could be a significant driver of natural gas demand in the medium term, the natural gas industry has an incentive to support measures to increase the adoption of NGV. Moreover, the government might support NGV diffusion. Government support, however, should only be

* In this paper, natural gas and all other fuel and powertrain options are displayed in energy units to allow for an easier comparison. Usually, the compression pressure of natural gas in fuelling stations amounts to 25 megapascal (MPa) and to 20 MPa in NGV tanks [29].

considered if it can be justified with the positive impacts of NGV diffusion [39] such as NGV′s emission reduction potential. The risks of misallocations [21] as well as long-term effects of such measures should be kept in mind when deciding on government interventions.

Especially with respect to potential customers, incentives may be required to increase adoption of the technology. Providing other incentives for NGV diffusion may not be successful unless there are enough filling stations offering natural gas to satisfy customer needs [24]. To reach the identified critical mass of at least 10% to 20% of currently existing conventional petrol stations, 1,450 to 2,900 natural gas stations have to be added to the existing 860 filling stations offering natural gas. In the medium to long term, this quantity of natural gas stations requires between 290,000 and 580,000 NGV (station-to-vehicle ratio of 1:200) and the quadruple of these numbers (for a station-to-vehicle ratio of 1:800) to make natural gas stations profitable.

In order for an adoption to happen at this scale, the economic advantage of NGV and its perception by vehicle drivers need to be ensured. Tax incentives for natural gas as a fuel contribute significantly to the cost effectiveness of NGV. Thus, a clear political commitment to natural gas as a medium term technology option in road transportation and continued tax incentives for natural gas would reduce the economic risk and promote the adoption of NGV considerably [8]. As long as the purchase of NGV still involves higher initial investment costs, subsidies (or tax credits) for NGV could promote NGV diffusion [8]. Moreover, labelling fuel prices in energy instead of volume and mass units would increase the visibility of natural gas' cost advantage for customers. Publicity, technological improvements in CNG storage technology and a greater amount of NGV models could further increase NGV adoption.

Scenario analysis

To estimate the emission reduction potential of NGV in Germany, we perform a scenario analysis comparing a reference scenario to a scenario with maximum diffusion of NGV (NGV scenario). The scenarios follow a bottom-up approach deducing energy demand from parameters such as the vehicle stock and the intensity of usage of energy consuming capital goods – in the case of this paper, of vehicles in road transportation [40]. Thus, the diffusion of NGV use in the NGV scenario is not an exogenous variable but is compiled considering vehicle stock developments. This requires a low level of aggregation.

General assumptions for the analysis in this article, such as projections of fossil fuel prices and energy demand are based on the International Energy Agency's (IEA) Reference scenario of the World Energy Outlook (WEO) 2009 [15]. Data from the National Technical University of Athen's (NTUA) Primes baseline scenario [13] was used to break down the WEO's data on energy demand to the national, sectoral (transport) and sub-sectoral level (road transportation) for all member states of the EU. Data was further enriched with assumptions on the development of – inter alia – vehicle categories and the fuel mix in road transportation in scenario analyses from Prognos and Oeko-Institut [17]. This allows for the more detailed scenario design necessary for the construction of the envisaged fuel switch scenarios in the transport sector. To make scenario analyses more reliable, the vehicle categories passenger cars and road freight transport were modelled individually. The shares of biofuels in petrol and diesel were deduced from data on the total fuel mix [17]. For reasons of data availability and significance, the average fuel mix was assumed for fuel tourism as well as for motorised two-wheelers and public transport. Differences between the sum of energy consumption of passenger cars and road transportation on the one hand and total energy consumption in road transportation on the other hand result from the energy consumption of motorised two-wheelers, public transport and fuel tourism.

Reference scenario

For our Reference Scenario, the described calculations yield a final energy consumption of 51.91 Mtoe in 2010 and of 49.04 Mtoe in 2030 in road transportation in Germany. Diesel and petrol have the biggest share in the fuel mix (see fig. 2).

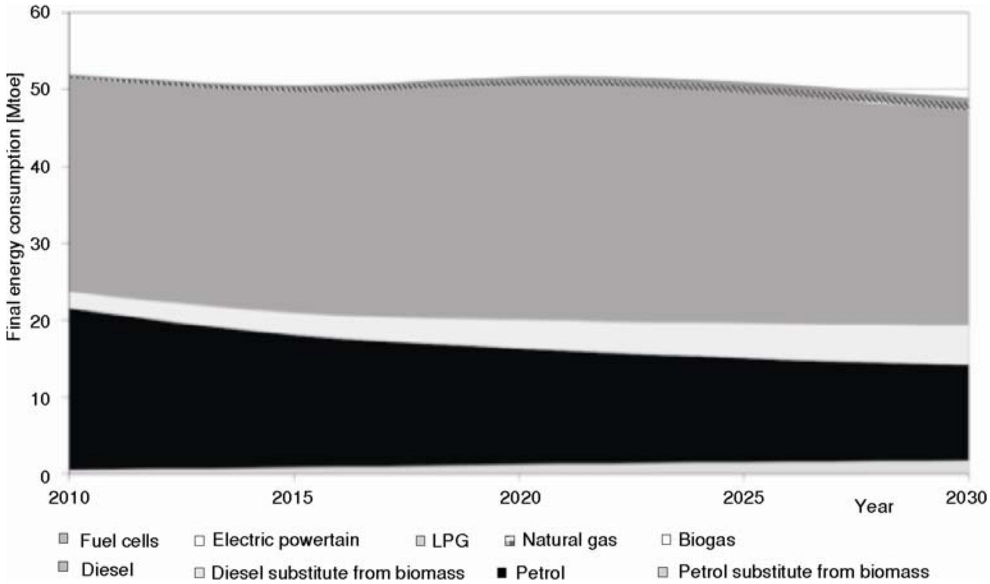

Figure 2. Reference scenario: final energy consumption by fuel and powertrain option in road transportation 2010-2030 (in Mtoe)

From 2010 to 2030 petrol consumption decreases from 27.8 billion l to 18.2 billion l whereas the use of diesel rises from 35 billion 1 to 38.9 billion l. The share of natural gas in the fuel mix quadruples over this time period but remains very small in absolute terms (893 kt in 2030). The share of biofuels increases significantly in all three types of fossil fuels. Improvements in fuel efficiency in the reference scenario are assumed to result in reductions of specific fuel consumptions ranging from 22% (diesel) to 25% (natural gas) in passenger cars and from 11% (LPG) to 18% (petrol) in road freight transport in the relevant time period [17].

To model the replacement of the vehicle stock, relative assumptions on future developments of vehicle stock by fuel and powertrain option [17] are applied to data on the current rolling stock from the German Federal Motor Transport Authority (GFMTA) [41]. Combining the two datasets results in a 3% increase in passenger car numbers from 41.7 M in 2010 to 42.7 M in 2030; the road freight transport vehicle stock increases by 11% from 4.3 M in 2010 to 4.8 M in 2030. With only 728 thousand passenger cars and 88 thousand in road freight transport vehicles in 2030, the share of natural gas fuelled road transportation remains small.

NGV scenario

In order to evaluate the emission reduction potential in road transportation, a NGV scenario is designed for comparisons with the reference scenario in the following section. The NGV scenario incorporates increases in rolling stock and is based on the maximum rate of diffusion which equals the natural replacement rate of the rolling stock, if conversion of existing vehicle stock into NGV is neglected. The NGV scenario assumes that as of January 2010 all obstacles for NGV diffusion are eliminated and consumers thus always choose NGV when buying a new vehicle. Thus, all newly registered vehicles are natural gas driven. The option to retrofit conventionally fuelled vehicles is not included in this theoretical consideration; the use of biogas is not accelerated in the NGV scenario.

To determine the replacement process of the vehicle stock from which final energy demand is calculated, further assumptions regarding future developments in the vehicle stock until 2030 are required. Separate stock models are developed for passenger cars and road freight transport. For these stock models, functions are estimated which express the stock development of vehicles by year of registration. These functions depend on time, the size of the rolling stock and the vehicle category and are based on historic data on vehicle stock from the German Federal Motor Transport Authority [41] for the years 1991 to 2010. The results of this approach are depicted in fig. 3 for passenger cars (for every second year). The graphs clearly replicate the asymptotic curve which is typical for the development of the vehicle stock registered in one specific year.

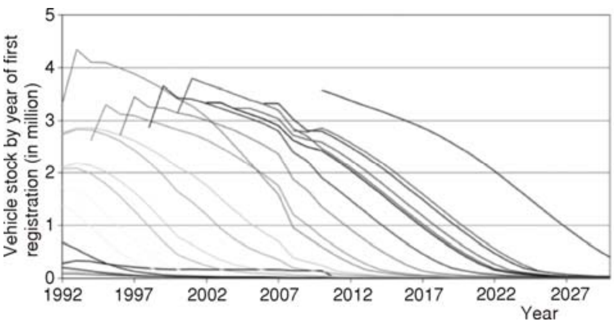

Figure 3. Development of vehicle stock 1992-2030 of passenger cars registered on January 1, 2010, by year of registration (in million)

In 2030, 1.3 of the 41.7 M passenger cars and 1.6 of the 4.3 M vehicles in road freight transport which were registered before January 1 2010 are still on the road. Vehicle stock development in the NGV scenario does not differ from the Reference scenario in absolute vehicle numbers by vehicle category but in their composition with respect to the fuel and powertrain option. To determine the vehicle stock categories' composition by fuel and powertrain option, first the growing share of NGV is calculated for both vehicle categories. For this purpose, the evolution of the pre-2010 vehicle stock (fig. 3) is subtracted from the total vehicle stock projection for both vehicle categories and all year in the considered time period. The results equal the number of vehicles which are registered for the first time after 2010 in both vehicle categories and each year. All of these vehicles are natural gas driven (see assumptions). The total number of NGV in both vehicle categories is determined for each year by adding the corresponding NGV from the pre-2010 stock to these numbers for each year in the considered time period. The disaggregation of the non-NGV stock into fuel and powertrain options is based on the relations between the other fuel and powertrain options according to the study Model Germany [17].

Under the NGV scenario's premise that all newly registered vehicles are natural gas driven, 97% of all passenger cars and 67% of all vehicles in road freight transport are natural gas driven in 2030. The replacement of conventionally fuelled vehicles is especially fast for passenger cars in the years up to 2020. Thus, in 2020 three quarters of all passenger cars are natural gas driven in the NGV scenario. The replacement of conventionally fuelled vehicles in road freight transport is considerably more moderate. Due to the lower replacement rate only 45% of all vehicles in road freight transport are natural gas driven in 2020.

Assuming the same values for the specific fuel consumption by vehicle category for both scenarios, the use of natural gas in road transportation increases significantly in the NGV scenario starting from 222 kt in 2010 and reaching a total of 35.225 kt in 2030. 24% of this amount are used in road freight transport (2030). In the same period of time, petrol use declines by 98% and diesel use by 73%. The difference between the two scenarios' natural gas use is considerable: Natural gas use in road transportation in this paper's Reference scenario accounts for only 2% of the NGV Scenario's in 2020 and only 2.5% in 2030.

As a consequence of the fuels' different heating values and the differing specific energy consumptions by vehicle category and fuel and powertrain option, the NGV scenario's fuel mix leads to a final energy consumption which is by 4.9% lower than the Reference scenario's. In 2030 36.9 out of 46.6 Mtoe of road transportation's final energy consumption are met by natural gas (Reference scenario: 0.9 out of 49.0 Mtoe), see fig. 4. Potential changes in final energy consumption caused by the replacement of other fuels by natural gas WTT are not considered in this analysis.

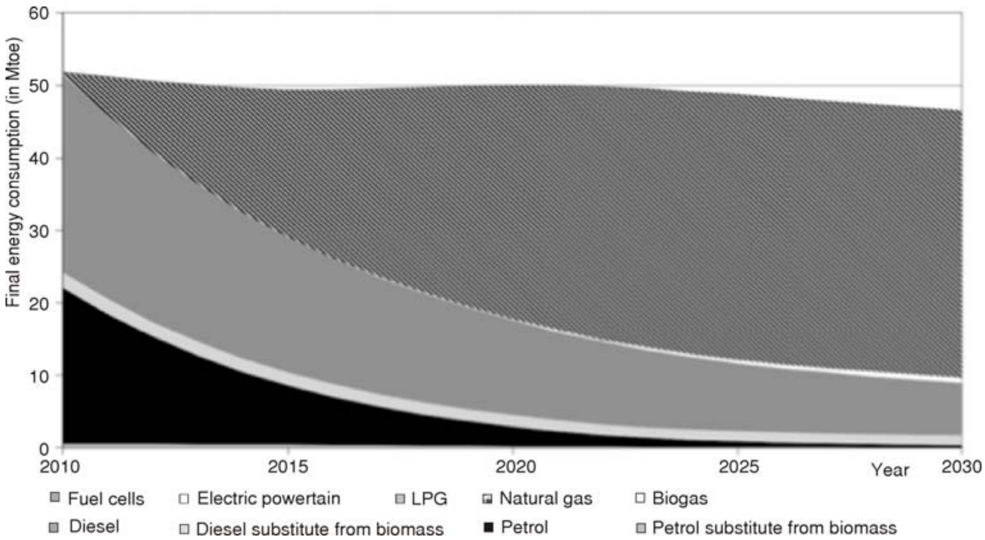

Figure 4. NGV scenario: final energy consumption of road transportation by fuel and powertrain option 2010-2030 (in Mtoe)

Emission reduction potential of NGV

Based on this detailed elaboration on a potential diffusion of NGV in road transportation, this section estimates the resulting emission reduction potential. Firstly, our calculations focus on the realisation of the NGV scenario in Germany and account for the emissions of the entire value chain of the fuel and powertrain options (WTW perspective). Subsequently, the results are extrapolated for the other countries of the EU. Finally, the emission reductions relevant for the German emission reduction target are determined. The section concludes with an evaluation of the effect of varying individual parameters and assumptions on emission reductions.

The calculations in this section are based on the final energy consumption in road transportation in the two scenarios and the specific emission factors of the different fuel and powertrain options. While most emission factors are assumed to be constant over time (see tab. 1), differentiations are made for the emission factor of natural gas due to its importance in this paper. Because of the depletion of natural gas fields in Europe over time and the growing demand in the NGV scenario, natural gas' emission factor is assumed to increase slightly from 66.5 g CO_2-eq./MJ in 2010 to 68.43 g CO_2-eq./MJ in the reference scenario and 69.26 g CO_2-eq./MJ in the NGV scenario in 2030. This paper's analysis is limited to emissions resulting from the direct use of the fuels and powertrain options: Emissions incurred by (re)constructing filling stations for NGV, additional gas supply infrastructure and other measures suggested for removing the existing barriers for NGV diffusion are not considered; neither are substitution effects in other sectors. It is further presumed that the production and maintenance of NGV does not cause additional emissions compared to those of petrol or diesel fuelled vehicles [42].

The analysis shows that the aforementioned fuel efficiency improvements in the reference scenario lead to WTW emission reduction of 10% from 186 Mt CO_2-eq. in 2010 to 167 Mt CO_2-eq. in 2030. In the NGV scenario, they decline by 26% to 138 Mt CO_2-eq. in 2030. Hence, emissions are 29 Mt CO_2-eq. lower in 2030 due to the use of natural gas. As fig. 5 shows, the emission reduction potential increases particularly quickly between 2010 and 2020. This is a result of the high replacement rate of passenger cars in this period of time and causes emission savings to reach 26 Mt CO_2-eq. in 2020 already compared to the Reference scenario.

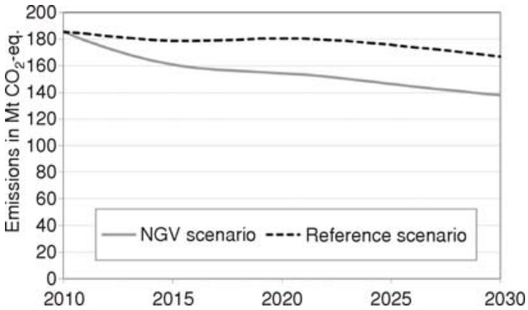

Figure 5. CO_2-eq. WTW emissions in road transportation in the Reference scenario and the NGV scenario 2010-2030 (in Mt CO_2-eq.)

Accumulated over the period under consideration the NGV scenario has the potential to reduce 464 Mt CO_2-eq. compared to the Reference scenario. Considering the vehicle categories, emission reductions are highest in passenger cars. In this vehicle category WTW emissions are reduced by 21% in the Reference scenario and by 35% in the NGV scenario until 2030. In road freight transport, WTW emissions actually increase by 7% in the reference scenario due to the increase in traffic in that category. The usage of natural gas as a fuel, however, also helps to reduce emissions in this vehicle category: In the NGV scenario, road freight transport's WTW emissions decline by 10% between 2010 and 2030.

To estimate the maximum emission reduction potential of NGV in the EU, the NGV scenario's emission reduction potential is extrapolated to the other member states of the EU using relations between the final energy demand in road transportation in EU countries from the Primes baseline scenario [13]. Differences between the EU countries' situation in transport, politics, economy and society are not considered. Thus, the results for the emission reduction potential in the EU are just a rough estimate based on the partial result for Germany. The extrapolations result in a WTW emission reduction potential of the NGV scenario of up to 165 Mt CO_2-eq. in 2030 compared to the Reference scenario and of about 2.5 billion t CO_2-eq. accumulated over the considered time period for the entire EU.

Finally, the emission reduction potential relevant for the German emission reduction target is determined. This requires a division of WTW emissions into WTT and TTW emissions. Because of a lack of data availability and relevance emissions resulting from tank tourism remain in Germany's emission balance. Under this premise all TTW emissions are domestic emissions. WTT emissions of petrol, diesel and natural gas are assumed to incur outside of Germany whereas the assumption is made that biofuels (petrol and diesel from biomass as well as biogas) are generated from domestic energy sources; thus their WTT emissions are attributed to Germany. WTT emissions of electric vehicles that result from power generation are imputed to Germany while WTT emissions caused by the extraction and transportation of the primary energy are assumed to arise outside of Germany.

Under the aforementioned assumptions, a share of 80% of the NGV scenario's WTW emission reduction potential is attributed to Germany in the first years of the time period under consideration and of 94% in 2030. Though emissions in road transportation have been decreasing in the last couple of years [1, 43] emissions in the Reference scenario in 2010 exceed 2009 emissions in road transportation in Germany by about 8% (158 *vs.* 146 Mt CO_2-eq.). This is mainly caused by the combination of the different sources of data used for this paper and the applied emission factors. Emissions decrease from 158 Mt CO_2-eq. in 2010 to 143 Mt CO_2-eq. (–9%) in the Reference scenario and 116 Mt CO_2-eq. (–27%) in the NGV scenario in 2030. This equals emission reductions that can be counted towards the German emission reduction target of 23 Mt CO_2-eq. in 2020 and of 27 Mt CO_2-eq. in 2030 compared to the Reference scenario. Accumulated over the time period under consideration, emission reductions in Germany amount to a total of 413 Mt CO_2-eq. While the emission reduction potential in road freight transport rises continuously, it declines slightly after 2025 for passenger cars. This is caused by the fact that the passenger cars' emissions in Germany in the Reference scenario decline, too, whereas they increase slightly in road freight transport. Furthermore, the diffusion of NGV in passenger cars is already highly advanced in 2025 (natural gas covers 94% of final energy demand in passenger cars) leaving little space for further expansions. In road freight transport, in contrast, less than half of the final energy demand is met by natural gas in 2025. The NGV scenario's total emission reduction potential compared to the Reference scenario is substantial.

Variation of assumptions

In the following subsection individual assumptions of the NGV scenario are varied one at a time and the effect on the emission reduction potential is evaluated for the years 2020, 2030 and on an aggregated level for the whole time period under consideration (tab. 3). Results are specified for WTW emissions and both vehicle categories (passenger cars and road freight transport).*

Firstly, we vary the rate of diffusion. This implies modifying the NGV scenario's assumption that the vehicle fleet is converted to NGV according to the natural replacement rate (consumers now no longer always choose NGV when buying a new vehicle). Instead, the

* As in the sections before, differences between the total values and the sum of the vehicle categories in tab. 3 can be attributed to tank tourism, public transport, and motorised two-wheelers. In the scenarios with varied assumptions, these were not assessed separately but are based on the relative values in the NGV scenario.

diffusion process is assumed to form a typical s-shaped diffusion curve. The maximum rate of diffusion is reached in the inflexion point and can at best reach the natural replacement rate of the vehicle fleet. Two variations of s-shaped diffusion curves are assessed.

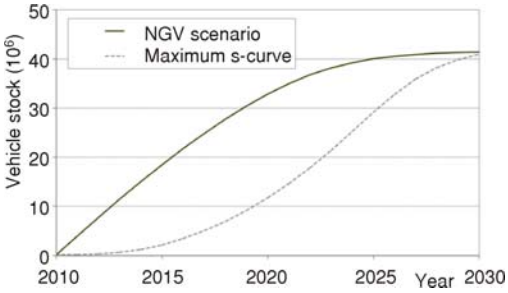

Figure 6. Vehicle stock natural gas driven passenger cars in the NGV scenario and with maximum s-curve 2010-2030

On the one hand, a maximum s-curve is chosen which reaches the maximum rate of diffusion in the inflexion point in passenger cars (Maximum s-curve, see fig. 6). Due to the lower natural replacement rate of the vehicle fleet in road freight transport the inflexion point in road freight transport is outside of the time period under consideration. With the Maximum s-curve, passenger cars reach their market potential in 2035, only slightly later than in the NGV scenario where natural gas driven passenger cars reach a market share of 97% in 2030. In the years before, the Maximum s-curve's results differ significantly from the NGV scenario's: At the beginning, the diffusion of natural gas in road transportation and the associated emission reduction are substantially lower than in the NGV scenario. In road freight transport values converge much later (tab. 3).

Table 3. CO_2-eq. emission reduction potential WTW with varied assumptions (in Mt CO_2-eq.)

Scenario	Vehicle category	Annual emissions 2020	2030	Aggregated emissions 2010 to 2030	Aggregated difference to Reference scenario	
Reference scenario	Total	180.5	166.7	3.732	–	–
	Passenger cars	114.9	100.5	2.387	–	–
	Road freight transport	63.4	64.4	1.316	–	–
NGV scenario	Total	154.5	137.7	3.269	–464	–12%
	Passenger cars	95.2	82.0	2.048	–339	–14%
	Road freight transport	56.9	53.8	1.187	–128	–10%
Maximum s-curve	Total	171.4	142.1	3.511	–222	–6%
	Passenger cars	106.4	82.2	2.198	–189	–8%
	Road freight transport	62.4	58.0	1.277	–39	–3%
Moderate s-curve	Total	179.0	161.3	3.686	–46	–1%
	Passenger cars	113.2	95.9	2.344	–43	–2%
	Road freight transport	63.0	63.1	1.306	–10	–1%
20% biogas	Total	145.6	117.1	3.075	–657	–18%
	Passenger cars	87.9	66.7	1.895	–492	–21%
	Road freight transport	55.4	48.8	1.149	–167	–13%

On the other hand, the effect of an s-curve with moderate diffusion of the NGV is assessed. For this Moderate s-curve, it is assumed that the NGV realise only 20% of the market potential of the Maximum s-curve in the same period of time before diffusion stagnates. This lower market penetration represents the higher end of the current situation in countries which have a large NGV stock [7]. At this stage of diffusion it can be assumed that the critical mass has been reached and that the diffusion of natural gas in road transportation is irreversible. The effects observed for the Maximum s-curve intensify with the Moderate s-curve and the emission reduction potential compared to the NGV scenario decreases significantly. Aggregated over the considered time period, emission reductions from the NGV compared to the Reference scenario decline by 6% with the Maximum s-curve and by only 1% with the Moderate s-curve, see tab. 3. The Moderate s-curve illustrates that emission reductions from the NGV fundamentally depend on the speed of the NGV diffusion.

Moreover, the effect of an increased use of biogas in road transportation is examined (tab. 3). It is assumed that the share of biogas in the fuel mix rises continuously and linearly reaching 20% in 2030 (2020: 10%). The additional emission reduction potential is considerable and can entirely be attributed to the German emission reduction target. While choosing alternative emission factors or the import of biogas would lead to different results, our assumption of domestic biogas production implies that almost another 200 Mt CO_2-eq. of road transport emission could be avoided until 2030 relative to the NGV scenario.

Conclusions

This paper has explored the potential of NGV as a bridging technology in low-emission road transportation in Germany. For this purpose, at first emissions and options for emission reductions in the transport sector as well as the current use of natural gas in road transportation and its prospects were illustrated. Furthermore, the diffusion process of NGV was described. After the main obstacles for the NGV diffusion resulting from the lack of a sufficient filling station infrastructure as well as vehicle characteristics and costs were identified, measures for eliminating these obstacles were presented. The second part of this paper concentrated on the development of a scenario analysis including a scenario with maximum diffusion of the NGV. This facilitated determining the emission reduction potential of the NGV in Germany relative to a Reference scenario.

Though the emission reduction potential of the NGV in Germany is considerable, it is not sufficient to reach Germany's long-term emission reduction target. While the maximum use of natural gas in road transportation could reduce transport emissions significantly, further emission reductions in natural gas based mobility could only be reached with efficiency improvements. These, however, are limited, too. Thus, the use of natural gas in road transportation can only be an option for short- to medium-term emission reduction efforts. As the transformation of the vehicle fleet and the relevant infrastructure would cause path dependencies, it is of crucial importance to keep this in mind when designing concepts for the mobility of the future.

To further evaluate the NGV as an option to reduce GHG emissions in the transport sector, an economic analysis would be of great value. Such an analysis would have to consider the costs of the NGV diffusion including capital costs for the transformation of the transport system to natural gas as well as changes in operating costs and the effects of higher natural gas demand on the natural gas market.*

* An economic analysis of the NGV as an option to reduce GHG emissions is forthcoming by the authors to complement the findings of this paper.

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