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Natural Gas in Road Transportation - A Low-emission Bridging Technology?[☆]

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Abstract

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 towards low-emission 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. A model-based analysis shows that the comparative cost advantage of natural gas relative to petrol and diesel per energy unit is not significantly reduced by the increased gas demand from natural gas vehicles. Capital costs for the transformation of the transport system to natural gas are therefore accompanied by lower fuel costs. Specific emission abatement costs of natural gas based mobility decline over time. After between 15 and 20 years, they are projected to be relatively low or even negative when a maximum rate of diffusion of natural gas vehicles is assumed.

Keywords: Emission reduction potential, Road transportation, Natural gas vehicles, Abatement costs, Low emission mobility, Alternative fuels

JEL classification: Q54, L92, Q41, O33

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1. Introduction

To mitigate climate change, the European Union (EU) focuses on 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 they are still far away from being market-ready.

This article explores the potential of natural gas as a bridging technology towards low-emission 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; the infrastructure to supply natural gas to filling stations all over Germany is largely in place. Specific investment costs are only slightly higher than those for conventionally fuelled vehicles. GHG emissions from natural gas-based road transportation are significantly lower than those of petroleum-based mobility. As a fossil fuel, the potential of natural gas to reduce emissions is limited. Nevertheless, if abatement costs are reasonable compared to other emission reduction options, it may contribute to lowering road transportation emissions in the next years until new, low-emission technologies are ready for the market.

An increased demand of natural gas in the transport sector may, however, also increase the costs of supplying natural gas if new resource deposits have to be tapped or if additional transport infrastructure investments become necessary. As a consequence, the cost of the application of the technology in the transport sector might increase. It is, hence, necessary for an analysis to take gas market effects into account.

This paper focuses on the quantification of the emission reduction potential of an intensified use of natural gas in road transportation and determines the costs and consequences of its realisation. 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, Section 3 outlines the barriers currently preventing a transformation of the transport sector from petroleum to natural gas-based mobility and provides an indication of what would be necessary to overcome these obstacles. We design a scenario with maximum diffusion of natural gas vehicles (NGVs) in road transportation assuming that all existing barriers were removed (Section 4). Comparison with a reference scenario allows for an estimation of the emission savings potential of natural gas-based mobility. Furthermore, we quantify the associated costs including repercussions on the natural gas market and calculate the abatement costs of the intensified use of natural gas in road transportation (Section 5). The final section offers some concluding remarks.

2. Emissions in Transportation and the Role of Natural Gas

The transport sector accounts for a significant part of global GHG emissions. In Germany, 153 m t (million tonnes) CO_2-equivalent (eq.) - 17 percent of the total 920 m t CO_2-eq. generated in Germany - fell upon the transport sector in 2009. With 146 m t CO_2-eq., 95 percent of all transport sector emissions accrued in road transportation (German Federal Environment Agency, 2011). 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) (Rodt et al., 2010).

The latter option is discussed in the paper at hand. Its implementation could, for instance, be achieved 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 (Edwards et al., 2007). 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. per megajoule (MJ)). Natural gas from regions like South-West Asia (4,000 km via pipeline) lies 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, natural gas generates 11 to 25 percent less emissions per unit of energy than diesel. The emission reduction per energy unit compared to petrol is somewhat smaller (see Table 1).

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 percent less reactive hydrocarbons than those fuelled with diesel (compared to passenger cars fuelled with petrol: -80 percent), 80 percent less nitrogen oxides (NOx; -20 percent), 50 percent less carbon monoxide (CO;

Table 1: Specific CO_2-eq. Emission Factors of Fuel and Powertrain options

Fuel / Powertrain Option	Emission in g CO_2-eq./ MJ		
	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[a]	-55.20	57.98	2.78
LPG (Liquefied Petroleum Gas)	7.97	66.19	74.16
Electric Powertrain	163.48	0.00	159.72

[a] Biogas with this specific emission factor is only available in limited quantities.

Source: Arithmetic average of values by Edwards et al. (2007); Richter and Lindenberger (2010) and German Federal Environment Agency (2010).

-75 percent), up to 99 percent less sulphur dioxide, carbon black and particulate emissions and up to 50 percent less noise emissions (Geitmann, 2008, 130-132). Furthermore, natural gas contains significantly less toxic components such as BTX and aldehydes and does not cause evaporation loss or odour nuisance during refuelling (Geitmann, 2008).

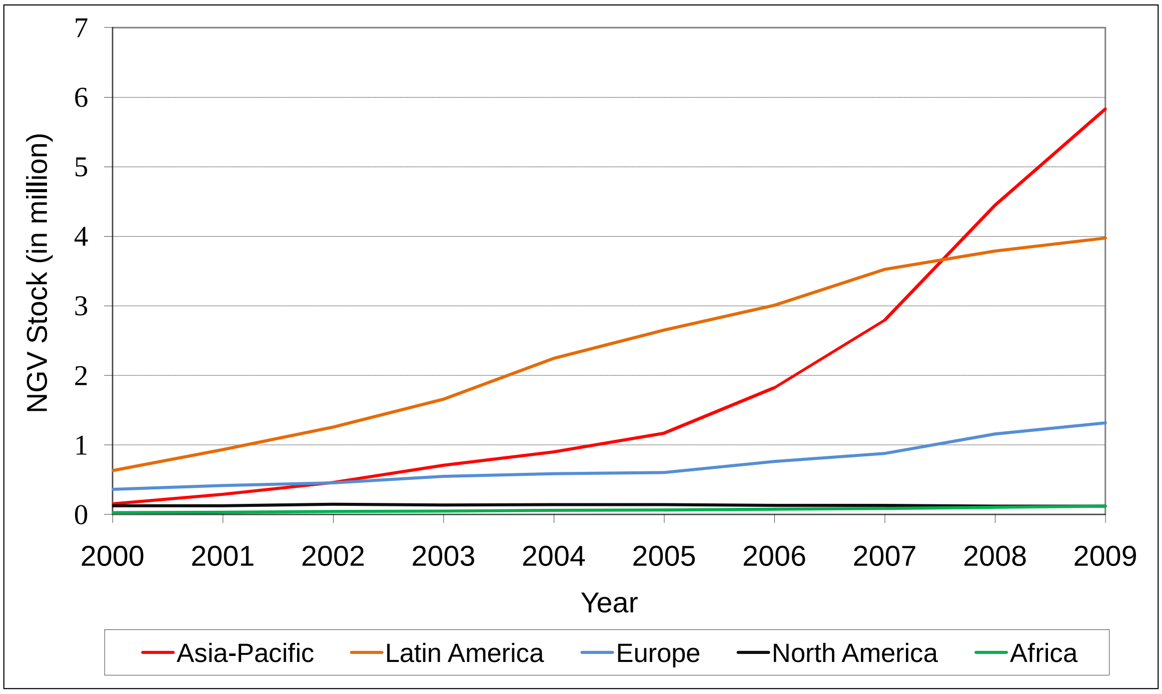
The mentioned advantages are some of the reasons why the global use of natural gas in road transportation has increased significantly since the early 1990s and especially since the turn of the millennium. At the end of 2009, 11.3 m NGVs were in use - nearly nine times as many as in 2000 (IANGV, 2010). While NGV growth rates are especially high in Asia and Latin America, rises in the usage of NGVs in Europe have so far been moderate (Figure 1). In 2009, 1.3 m NGVs operated in Europe.

According to the NGV industry association IANGV (2010), Pakistan currently has the largest NGV fleet globally with a total of 2.3 m NGVs and more than 3,000 natural gas stations. Between 1.6 and 1.8 m NGVs are in use in Argentina, Iran and Brazil while Italy has the largest number of NGVs in Europe (nearly 629,000 NGVs).

At the end of 2009, out of the 46 m vehicles registered in Germany, about 85,000 were powered by natural gas. 80 percent of these vehicles are passenger cars and 20 percent utility vehicles including 1,800 heavy-duty vehicles and buses. With 0.146 million tonnes of oil equivalent (Mtoe), natural gas covered 0.3 percent of the total fuel consumption in Germany in 2009 (DENA, 2010).

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 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 Table 2.

Figure 1: Development of NGV Stock Worldwide by Region (2000 to 2009)



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.

3. 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

Table 2: Share of Natural Gas in the Transport Sector / Road Transportation in Selected Studies

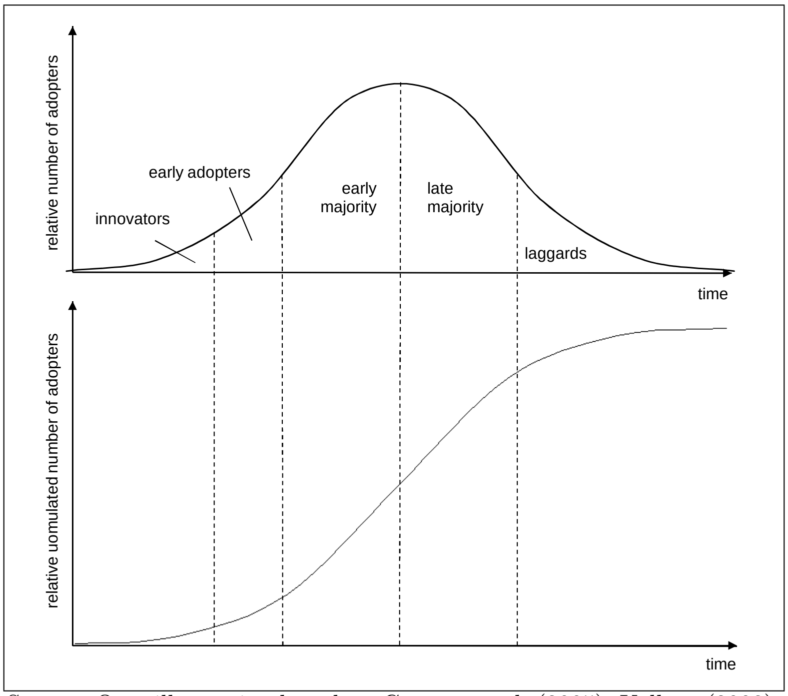
Share of natural gas [%]	2020	2030
Transport sector		
Germany		
"Energy Scenarios" (Nagl et al., 2010)	4.0 %	7.2 %
UBA-Long Term Scenario (Fischedick et al., 2002)	2.5%	5.2 %
UBA-Policy Scenario (Matthes et al., 2008)	0 - 2.2 %	0 - 3.7 %
"Energy Concept" (Lindenberger et al., 2008)	1.47 - 1.68 %	3.10 - 3.49 %
Primes (National Technical University of Athens, 2006b,a)	0.05 - 0.07 %	0.07 - 0.08 %

existing systems (modular vs. system innovations).[1]

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 (Hekkert et al., 2003).

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 NGVs - which is of great interest for the purpose of this work - equals the size of the market for road vehicles (Kellner, 2008).

Figure 2: Typical Adoption and Diffusion Curve



Source: Own illustration based on Corsten et al. (2005); Kellner (2008).

A typically s-shaped curve for a diffusion process over time is depicted in Figure 2. It illustrates that, generally, the diffusion of a technology starts rather slow (when so called innovators and early adopters adopt the technology, see Figure 2), accelerates until it peaks at an inflexion point and then declines steadily until

[1]See Capros et al. (2010); Corsten et al. (2005); Petermann (2000); Kellner (2008).

the technology's market potential is reached (Kellner, 2008). In 2009, only 0.3 percent of the total fuel consumption in Germany was covered by natural gas (DENA, 2010). 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. According to the European Commission (2001), only limited potential for NGV diffusion is expected to result from converting the current rolling stock into NGVs. In case conversion is neglected, the maximum rate of diffusion of NGVs 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 the critical mass is not reached, the number of adopters decreases again over time (see Petermann, 2000). For NGVs, 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 NGVs in Germany and outlines what would be required to remove them.

3.1. 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 NGVs are associated to the filling station infrastructure, vehicle characteristics and capital and operating costs.

Filling station infrastructure. NGVs 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 NGVs 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 percent of currently existing conventional petrol stations (see Yeh, 2007; Sperling and Kitamura, 1986). 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 (Schwoon, 2006). 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 percent) offered natural gas by the end of 2009 (IANGV, 2010). 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 (DENA, 2010) or at least between 400 and 800 (Carle et al., 2006) NGVs per filling station. Estimates vary because, among other reasons, assumptions regarding margins and fixed costs differ between the studies (Ramesohl et al., 2006). 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 according to Yeh (2007). 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 NGVs. With a ratio of 1 to 99, it is, hence, 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 NGVs: 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 NGVs.

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 (DENA, 2010). The maximum distance between two medium or high pressure gas pipelines is 40 km (Ramesohl et al., 2006) implying that even remote locations are never further away from an access to the natural gas grid than 20 km.[2]

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

The greatest advantage of NGVs 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 NGVs are an incremental innovation which can be observed and tried easily and which is proven (Borbonus et al., 2007), 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, according to Rogers (1995), generally has a positive impact on adoption.

However, natural gas as a fuel in road transportation also has properties which reduce the relative advantage of NGVs. 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 (Schüwer et al., 2010). 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 (see Geitmann, 2008; Mokhtarian and Cao, 2004). This characteristic may deter consumers from adopting the technology.

Additionally, only a limited amount of NGV models is currently available (DENA, 2010). This may particularly deter consumers with brand or model loyalty from buying an NGV and confirms the problem of a systemic innovation: Car producers only offer a limited supply due to small demand, but demand does

[2] Ramesohl et al. (2006) therefore estimates the capital costs for filling stations to offer natural gas amount are 190,000 EUR per station for the purchase and installation of the required additional equipment.

not increase because choice is limited.

Capital and operating costs. Capital and operation costs are a further crucial determinant for the adoption of NGVs. On the one hand, NGVs 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 NGVs 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 NGVs.

Currently, investment costs for NGVs 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 road transport vehicles depending on vehicle size.[3] With higher market penetration, investment costs are expected to decline in the future due to learning curves and economies of scale (Erdmann et al., 2006). Increasing emission standards also lead to rising costs for conventionally, especially diesel fuelled cars and improve the relative advantage of NGVs (DENA, 2010). Therefore, according to Erdmann et al. (2006), the additional capital costs of NGVs are expected to decline to between 150 and 1,200 EUR by 2020 depending on the market penetration of NGVs. 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 NGVs compared to petrol and diesel vehicles: Until the end of 2018, taxes for natural gas as a fuel in Germany are about 80 percent lower than those for diesel and about 65 percent lower than those for premium petrol. This contributes to significant fuel cost advantages for NGVs which amount to up to 50 percent compared to petrol and up to 30 percent compared to diesel vehicles depending on vehicle km travelled (DENA, 2010). 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 (DENA, 2010). Because of the tax advantage and lower commodity costs of natural gas, total operating costs are significantly lower for NGVs than for conventionally fuelled vehicles. Maintenance costs are only slightly higher for NGVs (Schubert and Fable, 2010).

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 (DENA, 2010). 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 (Yeh, 2007). Hence, most customers underestimate

[3] See DENA (2010); Carle (2006) for passenger cars. Own calculations for trucks and medium- and heavy-duty vehicles are based on Schubert and Fable (2010) and Hess (2007).

the actual cost effectiveness of NGVs. The combination of high capital costs and the biased perception of the actual cost effectiveness of NGVs poses another crucial barrier to diffusion of the technology in road transportation.

3.2. Removing the Barriers for NGV Diffusion

Measures to promote NGVs need to address the described barriers hampering the diffusion of NGVs. 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 NGVs resulting from the currently insufficient filling station infrastructure. However, it does not change the relatively high upfront investment costs of NGVs, 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 NGVs may be taken by all relevant stakeholders; a coordinated approach including various measures would increase the chances for success (Kellner, 2008). As NGVs 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 NGVs. Moreover, the government might support NGV diffusion. According to Hintemann (2002), government support, however, should only be considered if it can be justified with the positive impacts of NGV diffusion such as NGVs' emission reduction potential. The risks of misallocations (Kellner, 2008) 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 (Yeh, 2007). To reach the identified critical mass of at least 10 to 20 percent 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 NGVs (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 NGVs 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 NGVs. 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 NGVs considerably (DENA, 2010). As long as the purchase of NGVs still involves higher initial investment costs, DENA (2010) argues that subsidies (or tax credits) for NGVs could promote NGV diffusion. 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 variety of NGV models could further increase appeal to consumers and, hence, NGV adoption.

4. Scenario Analysis

To estimate the emission reduction potential of NGVs in Germany, we perform a scenario analysis comparing a Reference Scenario to a scenario with maximum diffusion of NGVs (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. 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.

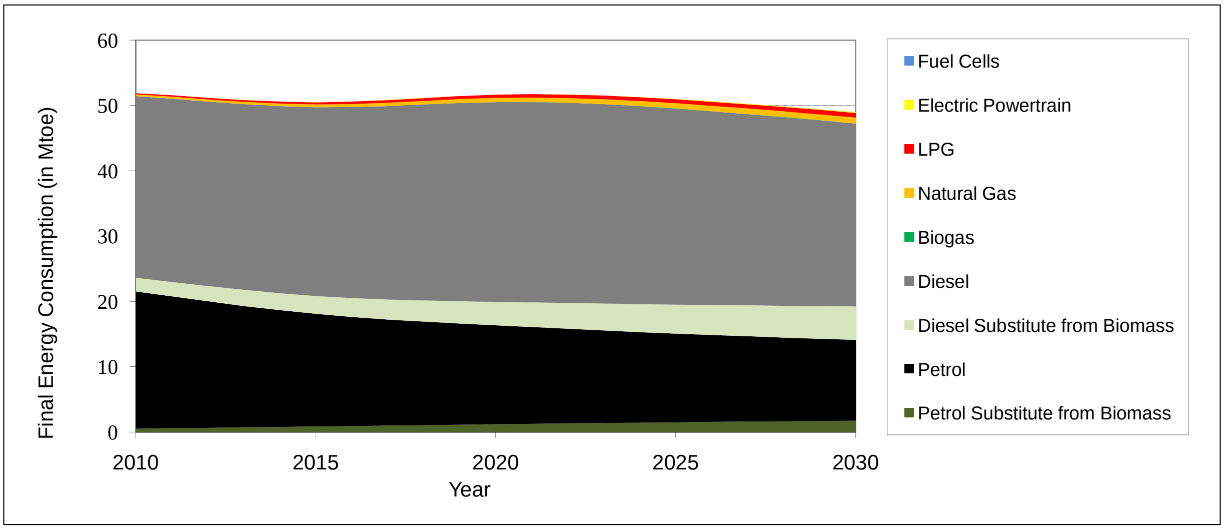
General assumptions for the analysis in this article, such as projections of fossil fuel prices and energy demand are based on the Reference Scenario of the World Energy Outlook (WEO) of the International Energy Agency (IEA, 2009). Data from the National Technical University of Athen's (NTUA) Primes Baseline Scenario (National Technical University of Athens, 2006b) 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 Öko-Institut (WWF, 2009). 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 according to the WWF (2009) study. 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.

4.1. 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 Figure 3 and Table C.8 in the Appendix).

From 2010 to 2030 petrol consumption decreases from 27.8 billion (bn) l to 18.2 bn l whereas the use of diesel rises from 35.1 bn to 38.9 bn l. The share of natural gas in the fuel mix quadruples over this time period but remains very small in absolute terms (893 million (m) kg in 2030). The share of biofuels

Figure 3: Reference Scenario: Final Energy Consumption in Road Transportation by Fuel and Powertrain Option



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 according to WWF (2009), see Table C.9 (Appendix). These range from 22 (diesel) to 25 percent (natural gas) for passenger cars and from 11 (LPG) to 18 percent (petrol) in road freight transport in the relevant time period.

To model the replacement of the vehicle stock, relative assumptions on future developments of vehicle stock by fuel and powertrain option from WWF (2009) are applied to data on the current rolling stock from the German Federal Motor Transport Authority (2010). Combining the two datasets results in a 3 percent 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 percent from 4.3 m in 2010 to 4.8 m in 2030. With only 728 thousand (k) passenger cars and 88 k in road freight transport vehicles in 2030, the share of natural gas fuelled road transportation remains small (see Table C.10 (Appendix)).

4.2. NGV Scenario

In order to evaluate the emission reduction potential in road transportation, an 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 NGVs is neglected. The NGV Scenario assumes that as of January 2010 all obstacles for NGV diffusion are eliminated and consumers thus always choose NGVs 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.

Figure 4: Development of Vehicle Stock of Passenger Cars registered on January 1 2010 by Year of Registration

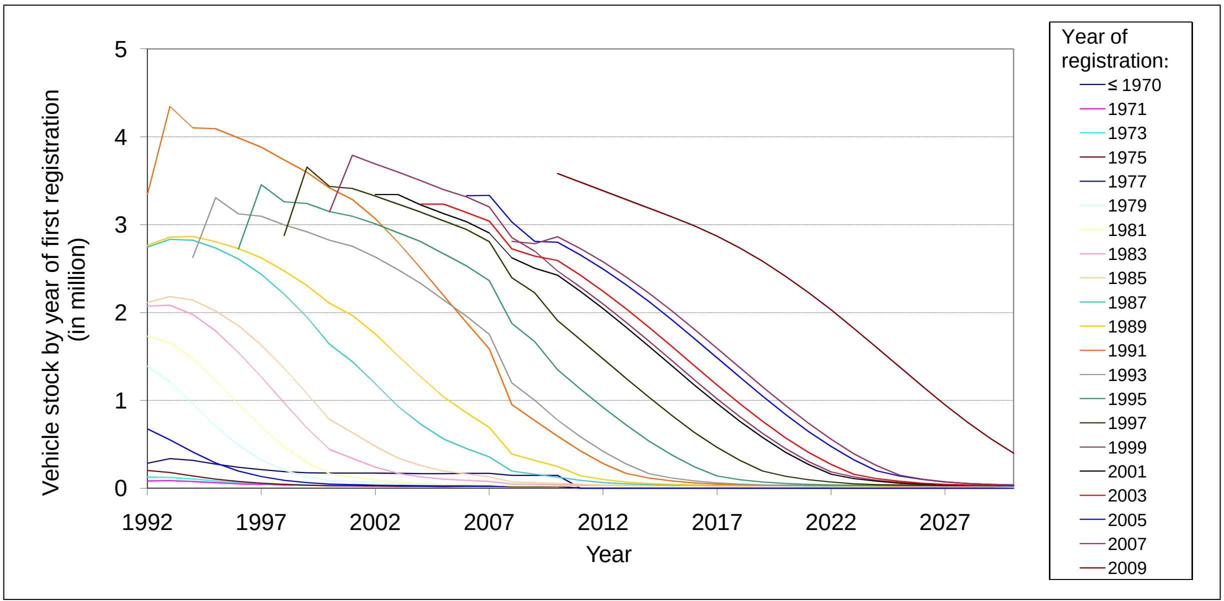
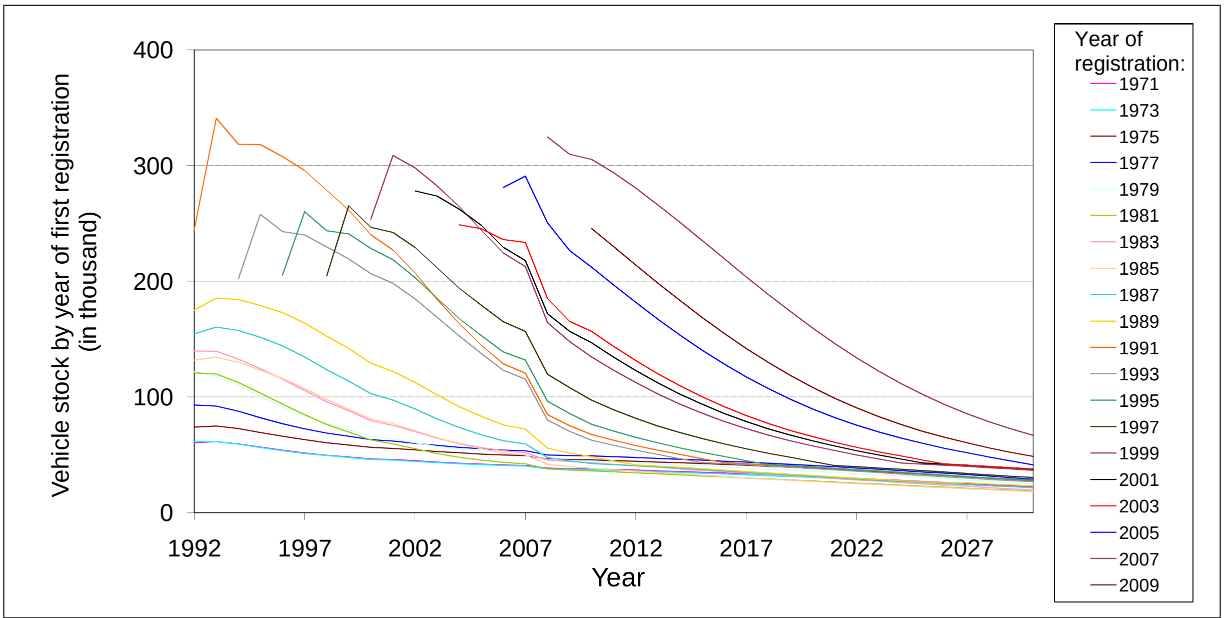


Figure 5: Development of Stock of Road Transport Vehicles registered on January 1 2010 by Year of Registration



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 (2010) for the years 1991 to 2010. The results of this approach are depicted in Figure 4 for passenger cars and in Figure 5 for road transport vehicles (for reasons of clarity 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.

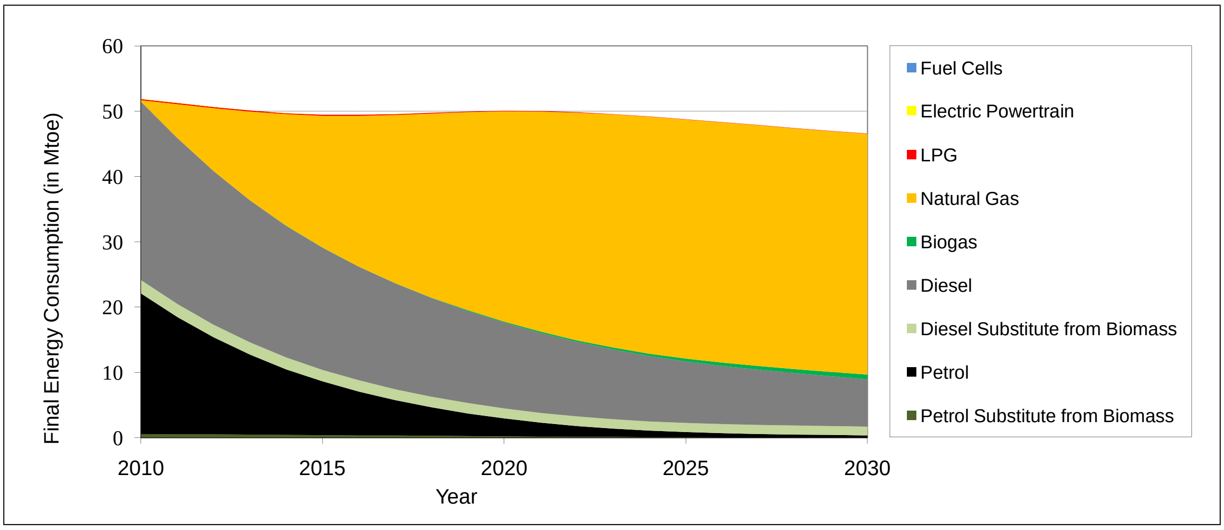
Table 3: NGV Scenario: Vehicle Stock by Vehicle Category and Fuel and Powertrain Option (in thousand vehicles)

Category / fuel	**2010**		**2020**		**2030**	
and powertrain option	Reference	[%]	NGV	[%]	NGV	[%]
Passenger Cars	**41,738**	**100%**	**43,160**	**100%**	**42,720**	**100%**
Petrol, without Hybrid	30,209	72%	6,270	15%	664	2%
Petrol, Hybrid	32	0%	169	0%	112	0%
Diesel	11,234	27%	3,733	9%	486	1%
NGV	149	0%	32,854	76%	41,420	97%
LPG	157	0%	99	0%	20	0%
Electric Powertrain	41	0%	34	0%	17	0%
Fuel cell	1	0%	0	0%	0	0%
Road Freight Transport	**4,345**	**100%**	**4,623**	**100%**	**4,847**	**100%**
Petrol	234	5%	76	2%	33	1%
Diesel	4,080	94%	2,458	53%	1,534	32%
Natural Gas	24	1%	2,080	45%	3,271	67%
LPG	5	0%	6	0%	6	0%
Electric Powertrain	3	0%	4	0%	4	0%

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. The composition of the vehicle stock per vehicle category by fuel and powertrain option is deducted using WWF (2009) (see Table C.11 in the Appendix for details). 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 NGVs is calculated for both vehicle categories. For this purpose, the evolution of the pre-2010 vehicle stock (Figure 4) is subtracted from the total vehicle stock projection for both vehicle categories and all years 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 NGVs in both vehicle categories is determined for each year by adding the corresponding NGVs from the pre-2010 stock to these numbers for each year in the considered time period. The disaggregation of the non-NGV vehicle stock into fuel and powertrain options is based on the relations between the other fuel and powertrain options according to WWF (2009) and under the assumption, that the stock of none of the other vehicle categories' fuel or powertrain options can increase (see Table C.12 in the Appendix for details).

Under the NGV Scenario's premise that all newly registered vehicles are natural gas driven, 97 percent of all passenger cars and 67 percent of all vehicles in road freight transport are natural gas driven in 2030 (see Table 3). 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 percent of all vehicles in road freight transport are natural gas driven in 2020.

Figure 6: NGV Scenario: Final Energy Consumption in Road Transportation by Fuel and Powertrain Option



Assuming the same values for the specific fuel consumption by vehicle category for both scenarios (see Table C.9), the use of natural gas in road transportation increases significantly in the NGV Scenario starting from 222 m kg in 2010 and reaching a total of 35,225 m kg in 2030. Twenty-four percent of this amount are used in road freight transport (2030). In the same period of time, petrol use declines by 98 percent and diesel use by 73 percent. 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 percent of the NGV Scenario's in 2020 and only 2.5 percent 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 4.9 percent 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 Figure 6 and Table C.13 (Appendix, page 35). Potential changes in final energy consumption along the value chain caused by the replacement of other fuels by natural gas are not considered in this analysis.

5. Results

Evaluating the potential of natural gas as a low-emission bridging technology in road transportation requires an analysis of its emission reduction potential and of abatement costs. Therefore, this section firstly presents the emission reduction potential of the NGV Scenario. To investigate specific abatement cost associated with the intensified use of natural gas in road transportation, the gas market needs to be taken into account due to potential effects on natural gas costs arising from the increased demand for natural gas (Section 5.2). Subsequently, section 5.3 evaluates the societal costs of NGVs to provide an overview of the specific GHG abatement costs.

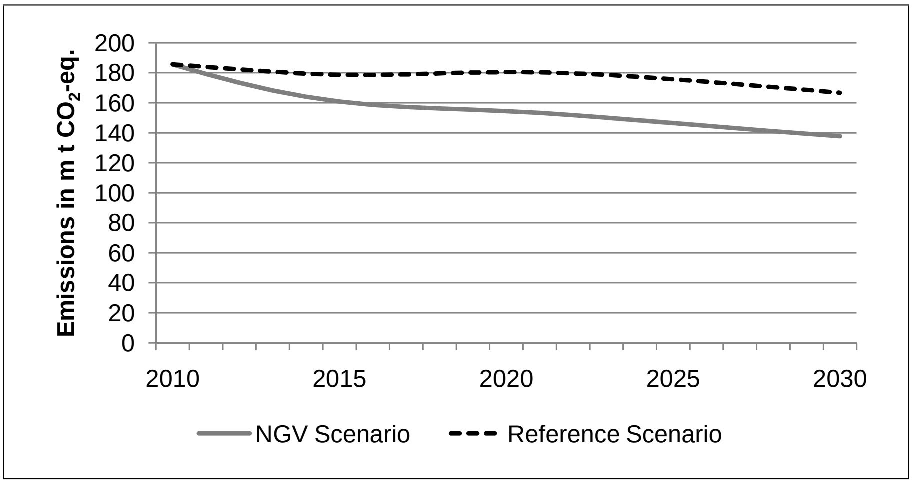
5.1. Emission Reduction Potential of NGVs

Based on this detailed elaboration on a potential diffusion of NGVs 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 to provide an estimate of the mitigation potential NGVs have EU-wide. 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. Scenario variations with different rates of NGV diffusion are analysed in Appendix Appendix B.

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 Table 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 has to be imported via longer distances in the future, especially in the NGV Scenario. This causes an increase in the WTT emissions of natural gas (see also Section 5.2). Thus, we assume that the specific WTW emission factor of natural gas increases 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 NGVs, 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 NGVs does not cause additional emissions compared to those of petrol or diesel fuelled vehicles Chester and Horvath (2007).

The analysis shows that the aforementioned fuel efficiency improvements in the Reference Scenario lead to WTW emission reduction of 10 percent from 186 m t CO_2-eq. in 2010 to 167 m t CO_2-eq. in 2030. In the NGV Scenario, they decline by 26 percent to 138 m t CO_2-eq. in 2030. Hence, emissions are 29 m t CO_2-eq. lower in 2030 due to the use of natural gas. As Figure 7 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. Thus, annual emission savings increase quickly and reach 26 m t CO_2-eq. in 2020 already compared to the Reference Scenario.

Figure 7: CO_2-eq. WTW Emissions in Road Transportation in the Reference and NGV Scenario



Accumulated over the period under consideration the NGV Scenario has the potential to reduce 464 m t 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 percent in the Reference Scenario and by 35 percent in the NGV Scenario until 2030. In road freight transport, WTW emissions actually increase by 7 percent 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 percent between 2010 and 2030.

To estimate the maximum emission reduction potential of NGVs 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 (National Technical University of Athens, 2006b). 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 m t CO_2-eq. in 2030 compared to the Reference Scenario and of about 2.5 bn 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 percent 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 percent in 2030.[4] Emissions decrease from 158 m t CO_2-eq. in 2010 to 143 m t CO_2-eq. (-9 percent) in the Reference Scenario and 116 m t CO_2-eq. (-27 percent) in the NGV Scenario in 2030. This equals emission reductions that can be counted towards the German emission reduction target of 23 m t CO_2-eq. in 2020 and of 27 m t CO_2-eq. in 2030 compared to the Reference Scenario (-19 percent). Accumulated over the time period under consideration, emission reductions in Germany amount to a total of 413 m t 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 NGVs in passenger cars is already highly advanced in 2025 (natural gas covers 94 percent 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.

[4] Though emissions in road transportation have been decreasing in the last couple of years (see German Federal Environment Agency, 2011; Kolodziej, 2009), emissions in the Reference Scenario in 2010 exceed 2009 emissions in road transportation in Germany by about 8 percent (158 vs. 146 M t CO_2-eq.). This is mainly caused by the combination of the different sources of data used for this paper and the deviation of their data from real developments as well as the applied emission factors.

5.2. Implications for the Natural Gas Market

A comprehensive assessment of the economics of NGVs requires a consideration of the effects of the increased gas demand. Generally, with an expansion of demand, gas prices may increase. This section aims to quantify potential price increases caused by the intensified use of natural gas in the transport sector. Substitution effects in other sectors and effects on costs for crude oil are not considered. As a reference, we apply the gas demand projection of the WEO (IEA, 2009).

Table 4: Natural gas demand in EU-27 in the Reference Scenario and the NGV Scenario

Gas demand [bcm]	2010	2020		2030		Increase in 2030
Country	Reference	Reference	NGV	Reference	NGV	due to NGVs
Austria	9.3	10.0	13.3	10.4	14.3	3.9
Belgium	15.5	17.3	22.3	19.3	25.3	5.9
France	44.1	44.4	72.1	47.9	81.3	33.3
Germany	85.1	88.1	122.9	97.5	137.1	39.7
Italy	83.1	91.0	111.7	104.2	127.8	23.6
Netherlands	38.9	39.3	45.7	40.4	48.2	7.8
Spain	38.3	38.5	59.1	35.4	62.0	26.6
Poland	15.7	19.8	28.2	25.5	37.2	11.7
United Kingdom	102.3	103.2	126.2	100.0	125.9	25.9
Others	93.2	101.2	136.5	119.3	165.8	46.5
Total	525.4	552.7	738.1	600.0	824.9	224.9

Source: Own calculations based on IEA (2009).

To model the impacts of increasing demand, we apply the global gas supply model MAGELAN by Seeliger (2006). The model is a spatial optimization model minimizing the costs of gas supply to all downstream markets. It is based on a production cost database of all relevant global production regions and can endogenously invest in natural gas production and transport infrastructure to satisfy consumer demand. Thus, it can be applied to estimate gas supply costs to consumers, as for instance done by Lochner and Bothe (2009). An update of the production cost database is provided by Lochner and Richter (2010). While such linear optimization models are not prognoses tools, they are particularly suitable for scenario analyses, i.e. the identification of effects from altering the presumptions.

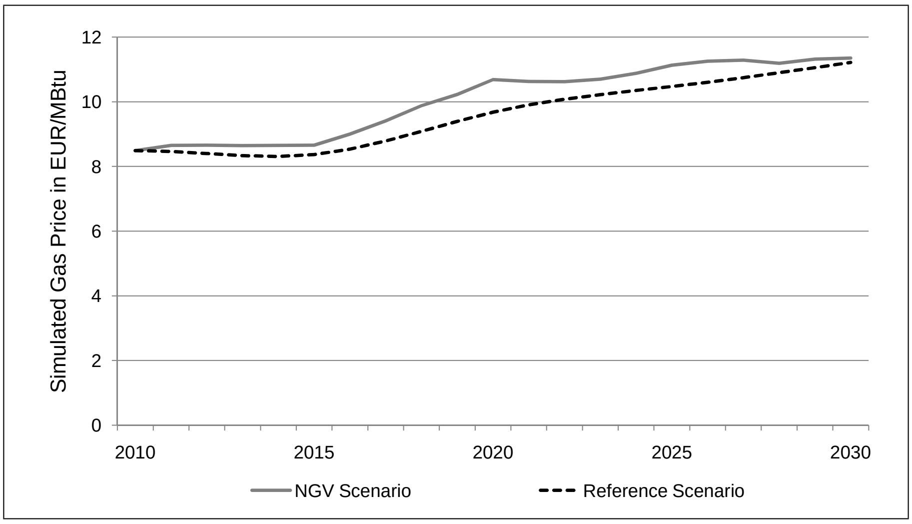
In the NGV Scenario, the increased demand for natural gas results from the emergence of a new field of application for natural gas. For Germany, additional demand for natural gas caused by NGV diffusion in the NGV Scenario amounts to 39.7 billion cubic metre (bcm) in the year 2030 and to 611 bcm accumulated over the time period from 2011 to 2030 compared to the Reference Scenario (IEA, 2009)[5]. This equates to an increase in demand for natural gas of 41 percent in 2030. Additional demand for natural gas rises the

[5]According to the WEO, NGVs only have a minor role in the transport sector and therefore do not cause significant gas demand.

fastest during the first ten years of the time period under consideration: In 2020, the additional demand already equals 40 percent of the Reference Scenario's demand for natural gas.

However, merely focusing on the extra demand caused by the NGV Scenario in Germany may underestimate the price effect of an increased use of NGVs on the gas market. In a globalising gas market with a projected volume of 4,313 bcm in 2030 (IEA, 2009), the additional demand resulting from the NGV Scenario in Germany amounts to less than one percent per year of the total global gas demand and therefore has a very limited price effect in the long term. Hence, we presume that if Germany adopts natural gas as a fuel in the transport sector, it is likely to gain importance in road transportation in other European countries as well. In 2030, an adoption of NGVs in road transportation in the EU similar to the one depicted for Germany in the NGV Scenario would imply an additional gas demand of 225 bcm[6]. While this amount is significant compared to the EU's demand for natural gas in the Reference Scenario (+ 37 percent), it equals only 5.2 percent of global demand for natural gas in 2030. Incorporating a substantial increase in natural gas demand in other countries of the EU as displayed in Table 4 may present a more realistic picture of potential price effects in the gas market caused by a spread of NGVs as depicted in the NGV Scenario for Germany.

Figure 8: Simulated natural gas price increase caused by NGV demand



Applying this gas demand scenario (Table 4) and the model configuration from Lochner and Richter (2010), we simulate the scenarios with respect to the price and source of the additional volumes in the NGV scenario. To estimate the price, we use the dual variables on the German energy balance constraints as

[6]The additional gas demand of the EU is extrapolated from the additional gas demand determined for Germany using relations between the final energy demand in road transportation in EU countries from the Primes Baseline Scenario (National Technical University of Athens, 2006b).

price estimator. In our linear program, they reflect the shadow cost of supplying one additional unit of natural gas at the respective location, i.e. the marginal cost. If the global gas market were competitive, this marginal cost would equal the price. To deduct the effect arising from increased NGV gas consumption, we calculate the difference of this variable in the NGV versus the Reference scenario. Results are depicted in Figure 8; our Reference Scenario price is based on IEA (2009).

Table 5: Total natural gas production increases 2011 to 2030

Region/ Country	Production increase [bcm]	[%]	Share of production increase
Africa	557	6.8	16.4%
Egypt	130	8.1	3.8%
Algeria	103	3.0	3.0%
Nigeria	153	7.0	4.5%
Others	172	17.0	5.1%
Asia-Pacific	15	0.2	0.5%
Europe	406	9.8	12.0%
Netherlands	138	12.9	4.1%
Norway	211	8.7	6.2%
Others	57	7.0	1.7%
CIS	1587	6.8	46.9%
Russia	946	5.4	27.9%
Turkmenistan	413	13.6	12.2%
Others	228	8.9	6.7%
Latin America	2	0.0	0.1%
Middle East	87	0.7	2.6%
North America	731	5.3	21.6%
World	3386	4.5	100.0%

It becomes evident that the increased consumption of gas in road transportation has a noticeable effect on marginal gas supply costs. However, in absolute terms, the difference peaks at 1.01 EUR/MBtu in 2020 and actually declines towards the end of the projection period. (By then, the exploitation of more expensive gas reserves is also necessary in the Reference case.) On average, the price in the NGV scenario in Germany is about five percent higher than in the reference case. The effect on the global gas supply balance in the projection period is displayed in Table 5. The table illustrates that the additional volumes are mainly produced in the countries of the former Soviet Union (Community of Independent States, CIS) and North America. Production is also higher in Africa, Europe and the Middle East, while it is not affected in the Asia-Pacific region or Latin America. With the largest extra volumes coming from Russia and Turkmenistan, it is clear that additional pipeline infrastructures to Europe are required. The investments in these assets and the production capacities are the main drivers of the cost increases depicted in the NGV scenario in Figure 8. Additional volumes in Europe also arrive as liquefied natural gas (LNG). The transport sector gas demand implies that they are diverted in the Atlantic Basin towards Europe causing larger investments in unconventional production technologies in the United States.

Concluding this excursion to the gas market we can, hence, state that the significant reserves in the global gas market are sufficient to supply the necessary gas volumes for European natural gas-based road transportation. Prices may increase, but only mildly so, as the global gas supply curve appears to be rather flat allowing a global expansion of production capacities, especially in Russia and North America.

5.3. Greenhouse Gas Abatement Costs of Natural Gas in Road Transportation

Relating the greenhouse gas emission reduction potential from NGVs to the cost of technology adoption yields the specific costs for each avoided tonne of CO_2-eq. We thereby take the cost of transformation (investment cost) as well as the cost of the application of the technology (fuel prices) into account.[7] Future expenses and savings are discounted; all values are reported in real EUR_{2010} prices.

INVESTMENT COSTS in technology adoption incur for gas station infrastructure and vehicles. As we presume the diffusion to occur through new vehicles (instead of upgrades of existing ones), we only need to take into account the extra costs for NGVs compared to petrol-fuelled cars. However, a differentiation of passenger cars and road transport vehicles is required because of large differences in these extra costs. As discussed in Section 3, we assume the extra cost of a passenger car to be 3,000 EUR in 2010 and 22,000 EUR for a truck. Both extra costs decline over time, to zero for cars and 10,000 EUR for trucks in 2030. For filling station investment costs, we use the Ramesohl et al. (2006) assumption of 190,000 EUR per filling station. While the timing of the incurrence of the NGV investments is determined by the diffusion process (see Section 4), we assume the addition of filling stations to be linear until all stations are converted in 2030.

FUEL COSTS are a more important determinant in absolute terms. The consumed amounts of petrol, diesel and natural gas can be derived from our analysis in Section 4. The net-of-tax per-unit costs are defined as follows: Generally, fuel costs for natural gas and petrol potentially differ regarding the commodity price and distribution costs to the filling station in Germany.[8] For the natural gas commodity price, we apply the results or our analysis in Section 5.2, i.e. the slightly higher price of natural gas in the NGV versus the Reference Scenario. Diesel and petrol prices are derived via a regression analysis. Thereby we establish the relationship between historic crude oil prices and the import prices of petrol and diesel (see Appendix Appendix A) and subsequently compute future petrol and diesel prices based on the crude oil price projection of the IEA (2009). As incorporating oil price effects of NGVs is beyond the scope of this analysis, we do not differentiate diesel and petrol prices between the scenarios. Theoretically, lower demand could lead to lower prices. However, a counterargument might be that prices in the crude oil market are determined by OPEC

[7]Expenses necessary for the removal of further barriers for NGV diffusion such as promotion, technological improvements (e.g. in CNG storage) or an increase of available NGV models are not considered in this paper. Neither are smaller cost items relevant for natural gas-based mobility such as the costs of the energy required for compression natural gas etc. Including these costs would enhance the quality of NGV analysis in this paper but unfortunately exceeds the scope of our study.

[8]Taxes are excluded from our analysis of the societal costs and benefits of the technology.

which could adjust output to maintain the same price level. For the purpose of this study, the assumption therefore appears to be a sufficiently good estimate. Regarding distribution costs, we base our analysis on a study of energy costs for the German Federal Ministry of Economics and Technology (Frontier/EWI, 2010). According to this study, distribution costs average 6.10 EUR/MWh (1.79 EUR/MBtu) for natural gas and 0.05 EUR/litre for petrol and diesel (1.63 EUR/MBtu for petrol and 1.48 EUR/MBtu for diesel, which has a higher energy intensity). Hence, distribution costs are similar. With respect to commodity costs, a cost advantage of natural gas (per unit of energy) becomes evident: it costed 10.25 EUR/MBtu in 2010, while the cost of diesel and petrol was 19.48 and 22.02 EUR/MBtu respectively. Although the natural gas price increases more until 2030 (28 versus 17 %), it retains a cost advantage per unit of energy. (Please note that the per-kilometre transport advantage of natural gas is lower due to the lower energy efficiency of the technology.)

Discounting of the costs and benefits in emission reduction technologies has been the subject of an extensive economic literature, which mainly centres on the discounting applied in the Stern (2007b) review on the economics of climate change. A comprehensive discussion of the different arguments is provided by Quiggin (2008). While Stern applies a discount rate close to the real interest rate on low-yield government bonds, some of his critics argue that a market-based rate reflecting the real cost of capital for private investment should be taken into account. As we are primarily interested in the societal costs of natural gas as a bridging technology, we apply a real risk free interest rate of 1.85 percent, which was the real interest rate on German 10 year government bonds between 2001 and 2010.[9] Incidentally, this also happens to be the average of the different rates applied by Stern (2007a) which range from 1.6 to 2.1 percent. To illustrate the effects of discounting on the evaluation of the NGV technology, we also provide the results for a market based real rate of 5.5 percent (Quiggin, 2008).

The comparison of the costs of the scenarios is presented in Table 6, which includes the considered cost factors differing between our two scenarios, i.e. the operating (fuel) costs in both scenarios and the additional capital costs for NGVs and natural gas filling stations in the NGV Scenario. Fuel costs in the NGV Scenario in 2015 are already 18 percent lower than in the Reference Scenario due to the relatively lower costs of natural gas per energy unit (which more than outweigh the lower energy efficiency of NGVs). Capital expenditures of the NGV Scenario amount to as much as 15 bln EUR annually but decline to below 2 bln EUR per year after 2025 when most of the expenditures have been made and the higher investment costs of NGVs vs. petrol and diesel vehicles have largely diminished. The biggest cost component is thereby the additional cost of passenger vehicles at the beginning of the investigated time period and the extra costs of medium- and heavy duty vehicles over the whole period of time. Already eight years after the beginning

[9]Calculations based on inflation (Series ICP.M.U2.N.000000.4.ANR) and bond yield (FM.A.U2.EUR.4F.BB.U2_10Y.YLD) data from the European Central Bank (ECB, 2011).

Table 6: Abatement Costs of the NGV compared to the Reference Scenario

Reference Scenario	**2010**	**2015**	**2020**	**2025**	**2030**
Fuel consumption [million MBtu]					
Petroleum	832	684	614	539	490
Diesel	1,104	1,146	1,203	1,190	1,110
Natural gas	10	17	24	32	36
Fuel price [EUR/MBtu]					
Petroleum	22.02	19.86	22.05	24.32	25.93
Diesel	19.48	17.61	19.51	21.49	22.88
Natural gas	10.25	10.13	11.16	12.23	12.98
Total costs Reference Scenario [bln EUR]	39.924	33.937	37.280	39.060	38.573
NGV Scenario					
Fuel consumption [million MBtu]					
Petroleum	854	326	138	31	13
Diesel	1,083	741	559	374	287
Natural gas	9	802	1,203	1,453	1,463
Fuel price [EUR/MBtu]					
Petroleum	22.02	19.86	22.05	24.32	25.93
Diesel	19.48	17.61	19.51	21.49	22.88
Natural gas	10.25	10.42	11.99	12.89	13.11
Total annual operating costs [bln EUR]	40.012	27.878	28.373	27.517	26.094
Total annual capital costs of Adoption [bln EUR] of which	0.18	9.29	4.90	1.80	1.11
Passenger cars	0.08	5.39	2.20	0.16	0.00
Medium-/ heavy-duty vehicles	0.08	3.83	2.58	1.46	0.91
Filling stations	0.03	0.07	0.12	0.18	0.20
Total costs NGV Scenario [bln EUR]	40.197	37.167	33.275	29.322	27.199
Additional annual costs NGV [bln EUR]	+0.272	+3.230	-4.005	-9.738	-11.374
Discounted and aggregated additional costs incl. intermediate years [bln EUR]	**2010**	**2015**	**until 2020**	**2025**	**2030**
Risk free discount rate (1.85%)	0.27	37.91	33.43	-5.15	-43.76
Market-based rate (5.5%)	0.27	34.74	31.59	7.75	-11.78
Aggregated avoided emissions [Mt CO_2-eq.]	0.0	49.1	126.5	277.0	412.8
Specific emission abatement costs [EUR/t CO_2-eq.]					
Risk free discount rate (1.85%)	n/a	772.41	264.27	-18.60	-106.01
Market-based rate (5.5%)	n/a	707.87	249.69	27.99	-28.53

of the diffusion process, total costs are lower in the NGV Scenario than in the Reference Scenario.

To evaluate the specific costs per tonne of greenhouse gas emissions avoided, total abatement and its costs over time need to be regarded. As early conversion costs are high and emission reduction takes place over time, specific costs depend on how long NGVs are used as a bridging technology. By 2025, specific abatement costs have declined to between -19 and 28 EUR per tonne of CO_2-eq. depending on the assumed discount rate. By 2030, they are negative independent of the interest rate. However, the high initial specific abatement costs also illustrate that adoption of the technology is costly and only pays off after time; according to our parameterization after about 15 years.[10]

6. Conclusion

The analyses in this paper investigate the potential of natural gas as a bridging technology towards low-emission road transportation. Although the adoption of natural gas-based mobility has some economic as well as environmental benefits, findings from diffusion theory indicate that there are obstacles preventing a large-scale adoption of NGVs. These are of systemic nature: Few natural gas-powered vehicles imply that only a limited number of filling stations can profitably offer natural gas (low supply); few refilling opportunities mean consumers are not willing to switch to the technology because of a lack of refilling comfort (low demand). The same applies to the supply and demand for NGV models. However, the favourable characteristics of the fuel also imply that a diffusion process might take off if the obstacles were removed through coordinated measures by the gas industry, car manufactures and government bodies.

Our calculations show that with the maximum rate of diffusion (which equals the natural replacement rate of vehicles) as assumed in the NGV Scenario, three quarters of passenger cars could be natural gas-fuelled within ten years and almost 100 percent within 20 years. The diffusion rate for road freight transport vehicles is considerably lower. As the use of natural gas in road transportation causes significantly less emissions than petrol- and diesel-based mobility, GHG emissions would decline substantially with a diffusion of NGVs. The maximum abatement potential for Germany alone amounts to more than 20 m t CO_2-eq. annually eight years after the start of diffusion. In 2030, emissions in the NGV Scenario are 19 percent lower than in the Reference Scenario. Between 2010 and 2030, the aggregated emission reduction potential in the theoretical case designed in the NGV Scenario amounts to 413 m t CO_2-eq. in Germany. (If the rate of NGV diffusion is lower, emission reductions only become significant in the medium to long term.) Considering the difficulties

[10] In Appendix (Appendix B, page 30) of this paper, scenario variations with different rates of diffusion are presented. These affect the potential of the emission reductions achievable within a given time period considerably; see also discussion in Wang-Helmreich and Lochner (2011). Abatement costs are, however, not fundamentally different as most conversion costs are variable in the sense that they are only incurred for cars which employ the alternative technology. Only costs of the remodelling of the filling station infrastructure may incur without being followed by immediate emission reductions. However, their share of total costs is relatively low (2 percent); and some of these expenditures may actually be delayed if the rate of diffusion is low.

existing for reducing emissions in road transportation, this emission reduction potential is considerable. However, albeit being less emission-intensive than petrol- and diesel-based road transportation, NGVs still emit significant amounts of greenhouse gases. Therefore, the technology is not suitable as a long term low-emission solution for the transport sector.

With respect to costs, the analysis shows that the specific abatements costs of NGV diffusion as depicted in the NGV Scenario are high in the first years of NGV diffusion but decline over time and may become moderate in the long term. Although natural gas demand increases significantly, our model-based investigation of the gas market shows that supply is sufficiently abundant so that the increased demand leads to only very moderate price increases. Per unit of energy, natural gas prices remain significantly lower than petrol or diesel prices. However, the capital costs for converting road transportation to natural gas are significant and only pay off over time due to lower fuel costs. Numerically, our analysis yields that specific abatements costs are high initially because of the capital expenditures and decline significantly over time.

The application of natural gas in road transportation is an option to reduce emissions relatively quickly. Abatement costs then essentially depend on the duration the technology is applied. The high transformation costs incurred upfront imply that specific emission avoidance costs are high initially. A long application of the natural gas technology in road transportation is required in order to achieve low or moderate abatement costs. However, as the emission reduction potential of NGVs is limited and not sufficient to reach Germany's long term emission reduction target, it has to be questioned whether such a long-term application of a technology based on fossil fuels is sensible: In 15 to 20 years, other low or zero-emission technologies in road transportation may be available. 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.

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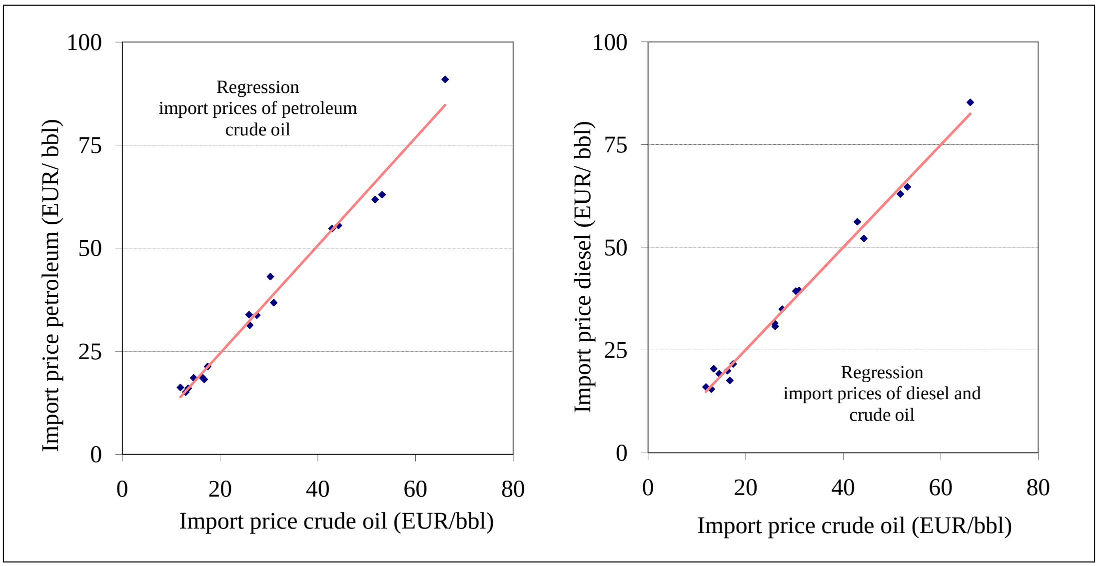
Appendix A. The Relationship between Petrol, Diesel and Crude Oil Prices

To estimate future petroleum and diesel prices for the scenario cost comparison, we perform a regression of historic petrol and diesel import prices from the Association of the German Petroleum Industry (MWV, 2010) on crude oil prices IEA (2009). Results are depicted in Figure A.9.

Figure A.9: Regression Petrol and Diesel price as a Function of the Crude Oil Price



The estimated coefficients for the respective prices (always in EUR/bbl) are:

$Petrol\ import\ price = -1.5801 + 1.3061 \cdot\ Crude\ oil\ price$

$Diesel\ import\ price = 0.065 + 1.2479 \cdot\ Crude\ oil\ price$

Appendix B. Scenario Variations with Different Rates of NGV Diffusion

In this appendix, individual assumptions of the NGV Scenario for Germany are varied to investigate their effect on the emission reduction potential are evaluated for the years 2020, 2030 and on an aggregated level for the whole time period under consideration (Table B.7). Results are specified for German road transportation WTW emissions and both vehicle categories (passenger cars and road freight transport).

At the focus of these sensitivity considerations is the rate of diffusion. This implies modifying the NGV Scenario's assumption that the vehicle fleet is converted to NGVs according to the natural replacement rate (consumers no longer always choose NGVs when buying a new vehicle). Instead, the 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.

Table B.7: CO_2-eq. Emission Reduction Potential WTW with Varied Rates of NGV Diffusion (in m t CO2-eq.)

Scenario (Category)	Annual emissions 2020	2030	Aggregation 2010 to 2030	Difference vs. Reference*	
Reference Scenario (Total)	**180.5**	**166.7**	**3,732**		
Passenger Cars	114.9	100.5	2,387		
Road Freight Vehicles	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 Vehicles	56.9	53.8	1,187	-128	-10%
Max S-Curve Diffusion (Total)	**171.4**	**142.1**	**3,511**	**-222**	**-6%**
Passenger Cars	106.4	82.2	2,198	-189	-8%
Road Freight Vehicles	62.4	58.0	1,277	-39	-3%
Moderate S-Curve Diffusion (Total)	**179.0**	**161.3**	**3,686**	**-46**	**-1%**
Passenger Cars	113.2	95.9	2,344	-43	-2%
Road Freight Vehicles	63.0	63.1	1,306	-10	-1%

*Difference in aggregated 2010-2030 emission compared to Reference Scenario

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). 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 percent in 2030. In the previous years, the Maximum S-Curve Scenario'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. As Table B.7 shows, values converge much later in road freight transportation.

On the other hand, the effect of an S-curve with moderate diffusion of NGVs is assessed. For this Moderate S-Curve Scenario, it is assumed that NGVs realise only 20 percent 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 (see IANGV, 2010). 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 with 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 NGVs compared to the Reference Scenario decline by 6 percent with the maximum s-Curve and by only 1 percent with the moderate S-curve, see Table B.7. The Moderate S-Curve Scenario illustrates that emission reductions from NGVs fundamentally depend on the speed of NGV diffusion.

Appendix C. Further Numerical Results

Table C.8: Reference Scenario: Energy Consumption in Road Transportation by Fuel and Powertrain option until 2030

[in Mtoe]	**2010**	**2015**	**2020**	**2025**	**2030**
Road Transportation (total)	**51.91**	**50.51**	**51.67**	**50.99**	**49.01**
Petrol vehicles	21.55	18.12	16.37	15.10	14.12
Petrol substitute from biomass	0.55	0.87	1.23	1.52	1.76
Petrol	20.98	17.24	15.14	13.58	12.36
Diesel vehicles	29.92	31.60	34.15	34.43	33.13
Diesel substitute from biomass	2.10	2.74	3.60	4.44	5.15
Diesel	27.83	28.89	30.58	30.01	27.99
NGV	0.25	0.43	0.64	0.81	0.94
Biogas	0.00	0.00	0.00	0.01	0.02
Natural gas	0.25	0.43	0.64	0.80	0.92
LPG	0.20	0.33	0.48	0.60	0.69
Electric power train	0.01	0.02	0.03	0.05	0.14
Fuel cell	0.00	0.00	0.00	0.00	0.00
Passenger vehicles	**35.43**	**33.28**	**32.92**	**31.56**	**29.55**
Petrol vehicles, w/o hybrid	22.03	18.16	15.94	14.16	12.55
Petrol substitute from biomass	0.57	0.87	1.19	1.43	1.57
Petrol	21.46	17.29	14.75	12.73	10.98
Petrol hybrid-vehicles	0.00	0.04	0.29	0.83	1.57
Petrol substitute from biomass	0.00	0.00	0.02	0.08	0.20
Petrol	0.00	0.03	0.27	0.74	1.37
Diesel vehicles	13.08	14.43	15.73	15.36	13.95
Diesel substitute from biomass	0.92	1.25	1.66	1.98	2.17
Diesel	12.16	13.18	14.07	13.38	11.78
NGV	0.18	0.34	0.51	0.65	0.74
Biogas	0.00	0.00	0.00	0.01	0.01
Natural gas	0.18	0.34	0.50	0.64	0.73
LPG	0.17	0.31	0.45	0.55	0.63
Electric power train	0.01	0.02	0.03	0.05	0.14
Fuel cell	0.00	0.00	0.00	0.00	0.00
Road freight transport	**16.82**	**16.97**	**18.10**	**18.74**	**18.89**
Petrol vehicles	0.26	0.19	0.14	0.11	0.10
Petrol substitute from biomass	0.01	0.01	0.01	0.01	0.01
Petrol	0.26	0.18	0.13	0.10	0.08
Diesel vehicles	16.50	16.67	17.80	18.43	18.56
Diesel substitute from biomass	1.16	1.44	1.88	2.38	2.88
Diesel	15.34	15.23	15.92	16.05	15.68
NGV	0.05	0.09	0.13	0.16	0.18
Biogas	0.00	0.00	0.00	0.00	0.00
Natural gas	0.05	0.09	0.12	0.15	0.18
LPG	0.01	0.02	0.03	0.03	0.04
Electric power train	0.00	0.00	0.00	0.00	0.01
Fuel cell	0.00	0.00	0.00	0.00	0.00

Table C.9: Specific Energy Consumption by Vehicle Category and Powertrain Option until 2030

	2010	**2015**	**2020**	**2025**	**2030**
Passenger vehicles					
Petrol vehicles, w/o hybrid (l/100km)	7.8	7.2	6.7	6.2	5.8
Petrol hybrid-vehicles (l/100km)	5.8	5.4	5.0	4.7	4.4
Diesel vehicles (l/100km)	6.3	5.8	5.4	5.1	4.9
NGV (kg/100km)	5.2	4.9	4.5	4.2	3.9
LPG vehicles (kg/100km)	5.7	5.3	4.9	4.6	4.3
Electric power train (kWh/100km)	19.4	18.2	17.0	15.9	15.0
Fuel cell (kg H2/100km)	1.7	1.5	1.4	1.3	1.2
Road freight transport					
Petrol vehicles (l/100km)	13.0	12.3	11.7	11.1	10.7
Diesel vehicles (l/100km)	22.3	21.2	20.4	19.9	19.4
NGV (kg/100km)	15.3	14.7	14.2	13.7	13.3
LPG vehicles (kg/100km)	16.2	15.8	15.4	14.9	14.5
Electric power train (kWh/100km)	54.0	52.1	50.4	49.0	47.5

Table C.10: Reference Scenario: Vehicle Stock by Vehicle Category and Powertrain option

[in thousand vehicles]	**2010**	**2015**	**2020**	**2025**	**2030**
Road Transportation (total)	46,083	47,074	47,783	47,968	47,567
Passenger vehicles	41,738	42,587	43,160	43,223	42,720
Petrol vehicles, w/o hybrid	30,209	28,078	25,991	23,919	21,474
Petrol hybrid-vehicles	32	99	701	1,918	3,626
Diesel vehicles	11,234	13,753	15,476	16,016	15,696
NGV	149	290	441	595	728
LPG	157	286	408	520	635
Electric power train	41	86	141	242	558
Fuel cell	1	1	2	2	3
Road freight transport	4,345	4,487	4,623	4,746	4,847
Petrol vehicles	234	179	137	113	100
Diesel vehicles	4,080	4,254	4,411	4,536	4,631
NGV	24	42	59	74	88
LPG	5	8	11	15	18
Electric power train	3	5	7	9	11

Table C.11: Development of 2010 Vehicle Stock until 2030

[in thousand vehicles]	**2010**	**2015**	**2020**	**2025**	**2030**
Road Transportation (total)	46,083	27,551	12,840	5,105	2,814
Passenger vehicles	41,738	24,217	10,274	3,101	1,242
Petrol vehicles, w/o hybrid	30,209	16,000	6,270	1,778	664
Petrol hybrid-vehicles	32	32	32	32	32
Diesel vehicles	11,234	7,837	3,733	1,190	486
NGV	149	149	106	44	23
LPG	157	157	99	39	20
Electric power train	41	41	34	18	17
Fuel cell	1	1	0	0	0
Road freight transport	4,345	3,334	2,566	2,004	1,599
Petrol vehicles	234	134	76	48	33
Diesel vehicles	4,080	3,168	2,458	1,924	1,534
NGV	24	24	24	24	24
LPG	5	5	5	5	5
Electric power train	3	3	3	3	3

Table C.12: NGV Scenario: Vehicle Stock by Vehicle Category and Powertrain Option

[in thousand vehicles]	**2010**	**2015**	**2020**	**2025**	**2030**
Road Transportation (total)	46,083	47,044	47,644	47,856	47,484
Passenger vehicles	41,738	42,557	43,022	43,112	42,639
Petrol vehicles, w/o hybrid	30,209	16,000	6,270	1,778	664
Petrol hybrid-vehicles	32	32	32	32	32
Diesel vehicles	11,234	7,842	3,733	1,190	486
NGV	149	18,484	32,854	40,055	41,420
LPG	157	157	99	39	20
Electric power train	41	41	34	18	17
Fuel cell	1	1	0	0	0
Road freight transport	4,345	4,487	4,622	4,744	4,845
Petrol vehicles	234	133	76	48	33
Diesel vehicles	4,080	3,169	2,458	1,924	1,534
NGV	24	1,177	2,080	2,765	3,271
LPG	5	5	5	5	5
Electric power train	3	3	3	3	3

Table C.13: NGV Scenario: Energy Consumption in Road Transportation by Fuel and Powertrain Option until 2030

[in Mtoe]	**2010**	**2015**	**2020**	**2025**	**2030**
Road Transportation (total)	**51.91**	**49.50**	**50.09**	**48.80**	**46.61**
Petrol vehicles	22.11	8.63	2.96	0.87	0.38
Petrol substitute from biomass	0.57	0.42	0.22	0.09	0.05
Petrol	21.54	8.22	2.73	0.78	0.33
Diesel vehicles	29.38	20.46	14.71	10.83	8.57
Diesel substitute from biomass	2.06	1.77	1.55	1.40	1.33
Diesel	27.32	18.69	13.16	9.43	7.24
NGV	0.23	20.24	32.32	37.05	37.62
Biogas	0.00	0.02	0.14	0.42	0.73
Natural gas	0.23	20.22	32.18	36.63	36.89
LPG	0.18	0.16	0.10	0.05	0.03
Electric power train	0.01	0.01	0.01	0.00	0.01
Fuel cell	0.00	0.00	0.00	0.00	0.00
Passenger vehicles	**35.28**	**32.67**	**32.13**	**30.58**	**28.70**
Petrol vehicles, w/o hybrid	21.91	8.39	2.72	0.70	0.26
Petrol substitute from biomass	0.56	0.40	0.20	0.07	0.03
Petrol	21.35	7.99	2.52	0.63	0.23
Petrol hybrid-vehicles	0.00	0.02	0.05	0.04	0.03
Petrol substitute from biomass	0.00	0.00	0.00	0.00	0.00
Petrol	0.00	0.02	0.05	0.04	0.03
Diesel vehicles	13.00	6.67	2.68	0.76	0.29
Diesel substitute from biomass	0.91	0.58	0.28	0.10	0.04
Diesel	12.09	6.09	2.40	0.66	0.24
NGV	0.18	17.44	26.60	29.04	28.11
Biogas	0.00	0.02	0.12	0.33	0.54
Natural gas	0.18	17.42	26.48	28.71	27.56
LPG	0.17	0.14	0.08	0.03	0.01
Electric power train	0.01	0.01	0.00	0.00	0.00
Fuel cell	0.00	0.00	0.00	0.00	0.00
Road freight transport	**16.63**	**16.52**	**17.21**	**17.44**	**17.26**
Petrol vehicles	0.20	0.19	0.16	0.11	0.08
Petrol substitute from biomass	0.01	0.01	0.01	0.01	0.01
Petrol	0.19	0.18	0.15	0.10	0.07
Diesel vehicles	16.37	13.61	11.69	9.78	8.08
Diesel substitute from biomass	1.15	1.18	1.23	1.26	1.26
Diesel	15.23	12.43	10.46	8.52	6.83
NGV	0.05	2.70	5.34	7.52	9.08
Biogas	0.00	0.00	0.02	0.09	0.18
Natural gas	0.05	2.70	5.32	7.44	8.90
LPG	0.01	0.02	0.02	0.02	0.02
Electric power train	0.00	0.00	0.00	0.00	0.00
Fuel cell	0.00	0.00	0.00	0.00	0.00

ABOUT EWI

EWI is a so called An-Institute annexed to the University of Cologne. The character of such an institute is determined by a complete freedom of research and teaching and it is solely bound to scientific principles. The EWI is supported by the University of Cologne as well as by a benefactors society whose members are of more than forty organizations, federations and companies. The EWI receives financial means and material support on the part of various sides, among others from the German Federal State North Rhine-Westphalia, from the University of Cologne as well as – with less than half of the budget – from the energy companies E.ON and RWE. These funds are granted to the institute EWI for the period from 2009 to 2013 without any further stipulations. Additional funds are generated through research projects and expert reports. The support by E.ON, RWE and the state of North Rhine-Westphalia, which for a start has been fixed for the period of five years, amounts to twelve Million Euros and was arranged on 11th September, 2008 in a framework agreement with the University of Cologne and the benefactors society. In this agreement, the secured independence and the scientific autonomy of the institute plays a crucial part. The agreement guarantees the primacy of the public authorities and in particular of the scientists active at the EWI, regarding the disposition of funds. This special promotion serves the purpose of increasing scientific quality as well as enhancing internationalization of the institute. The funding by the state of North Rhine-Westphalia, E.ON and RWE is being conducted in an entirely transparent manner.