In quest for a sustainable motorisation: the CNG opportunity

Andrea Stocchetti* and Giuseppe Volpato

Ca' Foscari University, Faculty of Economics,
Dept. of Business Economic and Management,
S. Giobbe – Cannaregio 873, I-30121 – Venezia – Italy
E-mail: stocchetti@unive.it E-mail: volpato@unive.it
*Corresponding author

Abstract: This article describes the opportunity deriving from the substitution of conventional fuels with the compressed natural gas (CNG). The advantages of this fuel are:

a relevant, as it concerns consumer's expenses and ecological aspect
b rapidly achievable
c close to hand for Europe, the USA and other countries where the motorisation is at the take-off stage, like the BRIC countries and Iran, Pakistan, Indonesia and so on.

These advantages makes CNG a viable solution, with relevant advantages both on the side of pollution and expenses, while waiting for the availability of new technologies.

Presently, the most important bottleneck for a large-scale implementation of this solution is represented by a possible shortage in the distribution network. Those countries crossed by gas pipeline could rapidly overcome this bottleneck without relevant costs. Otherwise, the solution could be achieved either through gas carrier's ships or through local production of biomethane by the exploitation of biomasses.

Keywords: sustainable motorisation; compressed natural gas; CNG; car industry; low emission cars.

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Biographical notes: Andrea Stocchetti is an Associate Professor of Business Economics and Management at the Ca' Foscari University. He participates in several national and international research projects related to the automotive industry. His main interest of research includes competitive analysis and supply-chain organisation. As a result of both empirical and theoretical research activities, he has published two books and about 50 national and international contributions between essays in books, articles and proceedings (http://www.unive.it/stocchetti).

Giuseppe Volpato is a Full Professor of Industrial Economics at the Ca' Foscari University. He is a Research Fellow of the International Motor Vehicle Program (IMVP) of the Massachusetts Institute of Technology di Boston, member of the Steering Committee of the Groupe d'Étude et de Recherche Permanent dans l'Industrie et les Salariés de l'Automobile (GERPISA), and a

Senior Adviser of the International Car Distribution Programme (ICDP). He is also a member of the editorial board for many national and international academic magazines (http://www.unive.it/volpato).

1 The need for a sustainable transport: the role of automotive industry

Although experts' opinion on the topic of ecological risks and global warming are extremely heterogeneous, the urgency of the reduction of all pollutants related to human activities and specifically, of those responsible for the greenhouse effect, is beyond any doubt. In 2007, the EU transport account for 28% of total CO_2 emissions, but this value grew by 35% between 1990 and 2006, while in the same period emissions from other sectors decreased by 9.4%. Vehicles in general are responsible for about 18%–20% of emissions and the European Environment Agency estimates that cars account for 14% of European CO_2 emissions [European Federation for Transport & Environment (T&E), 2008]. Thus, in all countries of the EU it is strongly rooted the general commitment towards the technical improvements of new cars and towards the implementation of models of transport capable of reducing both harmful emissions (CO, HC, NOx, PM) and CO_2, as one of the contributors to the greenhouse effect. The EU itself in 1993 has embarked on a path of gradual improvement of technical standards of cars in order to cut emissions; this road map is earmarked for 2015 as summarised in Table 1.

Table 1 Cars' emissions reduction goals according to Euro standards (g/km)

EU emission standard	*CO*		*HC/NMHC*		*NOx*	
	Gasoline	*Diesel*	*Gasoline*	*Diesel*	*Gasoline*	*Diesel*
Euro 1	2.72	2.72	-	-	-	-
Euro 2	2.20	1.00	-	-	-	-
Euro 3*	2.30	0.64	0.20/ -	-	0.15	0.50
Euro 4*	1.00	0.50	0.10/ -	-	0.08	0.25
Euro 5*	1.00	0.50	0.10/0.068	-	0.06	0.18
Euro 6*	1.00	0.50	0.10/0.068	-	0.06	0.08

EU emission standard	*HC + NOx*		*PM***	*Date*	
	Gasoline	*Diesel*	*Diesel*	*Homol.*	*Registr.*
Euro 1	0.97	0.97	0.1400	1.7.1992	1.1.1993
Euro 2	0.50	0.70	0.0800	1.1.1996	1.1.1997
Euro 3*	-	0.56	0.0500	1.1.2000	1.1.2001
Euro 4*	-	0.30	0.0250	1.1.2005	1.1.2006
Euro 5*	-	0.23	0.0050	1.9.2009	1.1.2011
Euro 6*	-	0.17	0.0045	1.9.2014	1.9.2015

Notes: *From Euro 3 on emissions are measured on at cold-engine start; ** Euro 6 introduces a limit on PM ($< 6 \times 10^{11}$ p/km).

Source: http://ec.europa.eu/enterprise/sectors/automotive/.

Although, for new cars the pollutants reduction is very considerable, in the coming years the overall degree of pollution in urban areas and city centres will remain very high due to the high share of older vehicles; specifically, only car introduced after the Euro 3 directive (that is, homologated after 1.1.2000 and registered after 1.1.2001) undertook severe anti-pollution standards.

Indeed, according to ACEA, in 2008, the average age of European car fleet was about 8–8.2 years and 30% of cars (that is: about 70 mln cars) are older than ten years; thus, it is likely that half of cars on the road in 2008 did not comply with Euro 3 standards.

In the case of the pollutant known as PM, several causes contribute to its diffusion, but human activities are the main ones: specifically, 30% of it is attributable to road transport and 25% to industrial activities. Within road transport, 13% of PM emissions come from light LDV (up to 3.5 tons), 9% from M/HDV, and the remaining 8% from cars.

Another important area of sustainability in which car industry is called to produce a major contribution is related to the CO_2 emissions. CO_2 is the main greenhouse gas[1]; the role of human activities in generating this gas might appear irrelevant, since only 3.5–4% of all CO_2 emissions are attributable to anthropogenic sources (Table 2).

Table 2 Global CO_2 emissions by source

Oceans	41%
Vegetation	27%
Ground	27%
Biomass combustion	1%
Human activities	4%
Global emissions	*100%*

	On global basis	On human activities
Power plants	1.00%	25%
Heating	0.92%	23%
Industrial activities	0.76%	19%
Biomass combustion	0.56%	14%
Vehicles	0.48%	12%
Other transports	0.28%	7%
Total	*4.00%*	*100%*

Source: VDI Association of German Engineers

Indeed, according to the majority of scholars, the relatively small percentage of CO_2 additionally generated by human activities has a destabilising effect on global climate, since this marginal increase triggers an increase in temperature that causes a further increase in CO_2 emissions from natural sources, thus, activating a vicious circle that almost all scientists in the field consider the main cause of the increased number of extreme meteorological events (e.g., hurricanes) as well as the cause of the raising of sea-level. Making a long story short, to prevent the degenerative global warming process, a relevant decrease in anthropogenic CO_2 emissions is necessary.

The European Union was initially committed, under the Kyoto Protocol, to reduce CO_2 emissions by 8% by 2008–2012 compared to the 1990 level. Moreover, in March 2007, EU leaders committed to a further 20%–30% overall reduction in greenhouse gas emissions by 2020 and in January 2008 the European Commission issued a package of proposals to legally implement these targets. The 'climate and energy package' is now working its way through the Council of Ministers and the European Parliament. Finally, the EU is committed to achieve at least a 20% reduction of its greenhouse gas emissions by 2020 compared to 1990 and is ready to reduce emissions by as much as 30% under a new global climate change agreement when other developed countries make comparable efforts. With the measures currently in place, EU-27 greenhouse gas emissions are projected to increase by 1% between 2006 and 2010, but with the implementation of additional measures, EU-27 emissions are projected to decrease continuously between 2006 and 2020. Nevertheless, current projections indicate that the EU-27 will not be able to reach the 20% reduction target (EEA, 2008).

In this framework, the role of car industry and transport sector in general is definitely crucial, in fact the transport sector as a whole is the worst performing sector as for the CO_2 emissions and seriously jeopardises the achievement of the EU commitment under Kyoto targets. The CO_2 emissions from transport in the EU grew by 35% between 1990 and 2006, while other sectors over the same period reduced their emissions on average by 3%. The share of transport in CO_2 emissions was 21% in 1990, but by 2006 this had grown to 28%. Moreover, transport is expected to present the greatest absolute increase in CO_2 emissions up to 2020 (Table 3), with 77 million tons, that is 61% of the overall increase from 2005 to 2020. Specifically, the European Environment Agency estimates that cars are responsible for 14% of overall European anthropogenic CO_2 emissions.

Table 3 Forecast change in CO_2 emissions 2005–2020 (mln tons per year)

Transport	+77
Residential	+26
Tertiary	+24
Industry	+19
Electricity and steam production	–8
Energy branch	–12
Total	*+126*

Source: EU (2007a)

As for CO_2, car makers' improvements are noteworthy too, although in 2008, only the sales of two brands (Fiat and Peugeot) went below the level of 140 g/km decided in the voluntary commitment signed by the ACEA (European Automobile Manufacturers Association) in 1998.

Actually, between 1997 (the first year in which car makers were required to provide CO_2 emissions data on the basis of official test-cycle) and 2008, the average emissions of the new cars sold in Europe by the ten major producers decreased on average by 17.2% and some producers (BMW, Peugeot and Fiat) decreased CO_2 emissions more than 20% (Table 4), a remarkable result although it depends mainly upon car makers' product range.

Car makers are involved in several plans to cut CO_2 emissions, especially with regards to the design and engineering of new low-emission cars. In December 2008, the European Parliament launched a measure which mandates the car makers to cut new models CO_2 emissions and impose monetary penalties for those exceeding the allowable limits (T&E, 2008a). But together with directives aiming at improving the offer it is also important to address vehicle demand towards those solutions that might drastically cut the level of pollutant in the very short term. This is of crucial importance, especially considering that the traffic intensity within cities will continue to increase because of the tendency of population to concentrate in big metropolitan area.

Table 4 Average CO_2 emissions of cars sold in Europe

	2008	*1997*	*1997/2008*
Fiat	134	169	–20.9%
Peugeot	138	177	–22.0%
Citroen	142	172	–17.2%
Renault	143	173	–17.5%
Toyota	145	163	–11.1%
Ford	148	180	–17.9%
Opel/Vauxhall	151	180	–16.1%
Volkswagen	159	170	–6.6%
BMW	161	216	–25.6%
Mercedes	185	223	–17.0%
Average	151	182	–17.2%

Note: By brand between 1997 and 2008 (g/km)

Source: T&E (2008)

The path towards alternative fuels might present a twofold advantage, considering that cars represent also an issue of sustainability from the economic point of view: 47% of all European oil utilisation is devoted to road transports. Oil imports for vehicles amount to 140 billion Euros a year, even more than the value added of the whole European automotive industry that in 2005, according to Eurostat, created value addition for 132 billion Euros (T&E, 2008).

2 Alternatives to conventional fuels

To accomplish the goal of cutting down pollutants and greenhouse gas, several tools and measures have to be adopted. A crucial role will be played by the introduction of low or zero-CO_2 emission like hydrogen, biofuels, as well as the introduction of electric cars in a context where power plants produce energy from renewable sources, like photovoltaic and wind-generators. But all these technologies will alleviate the pollution problem only in the medium-long term, because of a series of technical and/or economic constraints, while it is important to set up initiatives that can produce concrete results immediately. Thus, we claim that among possible short-term solutions, one of the best ways is the compressed natural gas (CNG) or compressed methane[2]. Alternative fuels that are usually taken into consideration are: hydrogen, biofuels, and electricity.

As for hydrogen, although it is constantly under the spotlight, being the zero-emission fuel by definition, it is not yet clears if, when and how it will be a real solution (that is, responding to all the technical and economical prerequisites that are necessary for a massive scale implementation). Presently, the most optimistic assessments predict a slight introduction of hydrogen engines by 2015 (Evans, 2008).

Biofuels of the present generation, like biodiesel and bioethanol, are obtained from agricultural food products by an ancient, relatively simple and well-known fermentation process; thus, the introduction of this fuel on a large scale would affect food prices (Rajagopal et al., 2007; FAO, 2008; Senauer, 2008). Thus, in order not to affect the prices of food raw materials require the development of biofuels of second, and third, generation obtained by cellulose of plant tissue or of oily algae. Such solutions are being tested but they require technology not yet sufficiently developed and whose development will still take some years. At the moment, biodiesel can be mixed with diesel up to 5% in volume in engines complying with UNI EN 14214 technical specification; the goal is to reach a 7% in volume (5.75% in energy) within 2010, but such goal requires different technical specifications. Biodiesel energy balance[3] is 2.5 at maximum (from sunflowers), while the average energy balance for bioethanol in Europe is 1.2, exceptionally far away from the value eight obtained by sugarcane in Brazil. The considerable variations in efficiency levels mainly depend on the raw materials and on the proximity of the crop area to the site of utilisation. The current thrust on bioethanol in the USA comes from the surpluses of maize production compared to domestic needs, while in the Italian case the raw material has been imported up to the present time, thus, the energy balance and even the CO_2 balance are likely to be negative (Nomisma Energia, 2008).

The electric car is considered a most promising field of development. The electric engine has the two fold advantage of being zero-emissions in the phase ‘pump-to-wheel’[4] and to have a very high efficiency: above 90%, compared to values ranging between 25% and 38% respectively for gasoline and diesel engines. In fact, this technology compensates in large part the low energy density of the source. Presently, the energy density of batteries still poses significant constraints to the development of electric vehicles competitive, in terms of performance and cost, with vehicles powered by conventional fuels. But this technology looks very promising already in the short-medium term, by virtue of the expected, significant improvements in batteries.

Electric vehicles are already present in several local niches and all around the world there are several producers of pure-electric vehicles designed for various purposes, including local mobility. But in fact pure electric cars are at the moment constrained into a very small niche, since the few models in the market are far from the commonly accepted threshold of performances/price ratio, specifically because the autonomy is far below that of a common car. Apart from Tesla, that have delivered its 700th vehicle in September 2009, and REVA, who allegedly sold 3,000 electric cars, major OEMs did not went further than selling few units of common cars adapted to electric power. Autonomy and supply remain the crucial points to be developed to make this technology attractive to consumers; various models, specifically conceived as pure electric-powered vehicles have been announced for 2010, with alleged better performances and innovative way of supply, but the market share of pure electric-vehicles will hardly reach 1% of market share before 2015.

Hybrid vehicles have demonstrated to be reliable and appreciated by consumers and their market share, although very small, is constantly increasing. The ideal conditions for hybrid vehicles are those of commuters living in the suburbs and working in a city centre or congested business district, when the electric engine comes frequently into operation and contributes to cut emissions in a typical high-polluted environment. But the overall contribution of hybrid cars in cutting emissions is instead very moderate. As a first, the real reduction in fuel consumption and in CO_2 emissions is strongly affected by the driving situations, specifically by the share of time in which the driving situations allow the use of electric engine. Indeed, the electric engine comes into operation for a relevant share of overall driving time in urban cycle and in the stop-and-go situations. If a high share of driving time occurs at cruising speed (typically on motorways or on extra-urban roads) then efficiency and emissions are equal to standard vehicles (IGU, 2005). The official emissions reported by hybrid vehicles are calculated on a driving-cycle (NEDC – New European Driving Cycle) of limited duration during which batteries are charged, but on a long journey the efficiency decrease significantly as long as batteries run down. Second: one should consider the trade-off between the advantages of the hybrid engine and the disadvantages (both economical and environmental) deriving from the batteries and the additional equipment. As for the environmental aspects, in this regard, pure electric vehicle would perform much better.

As for the costs, apart from the higher initial cost of both electric and hybrid cars, in both cases (hybrid and pure electric cars) batteries are costly and have to be replaced approximately every eight year in a hybrid car and every five years in an electric car. Thus, the commonplace that to refuel an electric car one spends ‘one euro’ or so it’s misleading since it does not take into consideration the cost of the progressive consumption of batteries.[5]

These technologies are almost certainly the answer to the problem of long-term sustainable mobility; on the other hand, CNG seems at the moment by far the most advantageous short-term solution from three crucial points of views:

a environment

b costs

c availability.

3 The ecological benefits of the CNG

The literature about the benefits of methane as fuel for vehicles is vast (Gas Research Institute, 1987; Liew and Liew, 1995; United Nations, 2003). In the USA, such solution is advocated mainly with regards to fleet for commercial and local transport use. Indeed, in countries where the cost of conventional fuel is high, CNG is a viable alternative for private cars too that potentially could effect sizeable cuts in harmful emissions.

NG is in fact a mixture of several natural gases (methane, buthane, ethane, etc.) where the share of methane is generally above 90%. Methane molecule consists of a tetrahedron structure in which a carbon atom binds to four hydrogen atoms; this leads to the excellent characteristics of the methane that in the presence of oxygen produces the highest amount of heat per unit mass.[6]

Moreover, methane has a high octane index, which allows a higher knock-resistance and therefore a higher efficiency of the engine.[7] These technical features allow CNG to have a higher heat of combustion (Table 5) and considerable lower emissions with regards to all main pollutants (Table 6).

Table 5 Index comparison among fuels

	Octane (RON)	*Heat of combustion (MJ/kg)*
Gasoline	95–100	44.0
Diesel	-	43.3
CNG	130	47.7

Source: IFP

Table 6 Comparison among fuels, in relation to Euro 5 standards (NEDC cycle) (g/km)

	NHMC	*NOx*	*PM*
Gasoline	0.068	0.060	0.003
Diesel	0.050	0.180	0.005
LPG	0.055	0.040	0.002
Methane	0.015	0.030	0.001

Source: Elaboration on EU data

Methane also presents lower CO_2 emissions in comparison with conventional fuels, this is also true for recent cars (on average, –23% in comparison to gasoline, –9.4% to diesel and –12.5% to LPG.[8] The difference is particularly evident in comparison with older cars (Euro 0 and Euro 1) and when used during the urban cycle (Table 7). According to the Italian National Council of Research (CNR, 2007), comparing the natural gas with Euro 4 in an urban cycle at the average speed of 25 km/h, methane provides significant environmental advantages against gasoline and petrol as regard to CO_2 (carbon dioxide) and diesel volatile organic compound (VOC) emissions (Table 7). The CNG CO_2 reduction compared to Euro 4 standard is around 20% on gasoline and about 30% on diesel, (Table 7). However, comparing the emissions of engines running on methane to the average emissions of old cars (Euro 0 and Euro 1 vehicles), there is a significant advantage on all these indicators. According to these data, in the urban cycle methane powered engines are 'dominant' with respect to petrol and diesel (that is: have better performances in any case) only as regards to CO_2 emissions. On the other hand, recent petroleum vehicles present much lower emissions of NOx and PM10 that are pollutants responsible for serious health damages. To make a long story short, one could say that the sooner are the cars converted to methane powered engines, the greater is their contribution towards environmental improvement.

In fact, these data provide an unambiguous indication in relation with the short-term effectiveness of a 'methanisation' (that is: conversion to methane) policy in the reduction of pollutants and greenhouse gas.[9]

The benefits deriving by the diffusion of methane as fuel can be demonstrated by simulating the average pollutants reduction deriving from the substitution of older cars with methane-powered ones. Thus, we have estimated the reduction of CO_2 and other pollutants that would occur in the Italian car fleet if the oldest 10% cars of the circulating fleet would be converted into methane-powered ones.

Table 7 Fuel comparison in the different Euro Standards

		NOx (g/km)	*VOC (g/km)*	*PM10 (g/km)*	*CO_2 (g/kWh)*
Euro standard '0'	Gasoline	1.79	2.04	0.040	243
	Diesel	0.63	0.23	0.260	235
	Methane	0.18	0.01	0.009	170
Euro standard '1'	Gasoline	0.26	0.26	0.040	220
	Diesel	0.55	0.08	0.073	235
	Methane	0.18	0.01	0.009	170
Euro standard '2'	Gasoline	0.09	0.05	0.011	220
	Diesel	0.55	0.08	0.073	235
	Methane	0.18	0.01	0.009	170
Euro standard '3'	Gasoline	0.06	0.036	0.008	220
	Diesel	0.37	0.023	0.014	235
	Methane	0.15	0.009	0.009	170
Euro standard '4'	Gasoline	0.033	0.007	0.004	220
	Diesel	0.122	0.019	0.008	235
	Methane	0.138	0.008	0009	170

Source: CNR (2007)

Table 8 shows the average CO_2 emissions of Italian circulating car fleet by class of displacement, fuel and Euro standard.[10]

Table 9 contains the composition of the fleet divided by the same criteria.[11]

According to these data, at the end of 2008 in Italy were circulating more than 5.1 million pre-Euro cars (14.3% of the whole fleet). The weighted average (w.a.) of CO_2 emission of this portion of the Italian fleet is 173 g/km (178 g/km for Euro 1), decreasing up to 147 g/km for Euro 4 (–15%), while the methane w.a. emission for Euro 0 fleet is 137 g/km (even lower than overall Euro 4 fleet average emission) and decreasing to 108 g/km for Euro 4 methane cars on the road (–215%). These data show that by installing a methane system, a Euro 0 car produces a reduction in CO_2 that is greater than substituting a Euro 0 car with a Euro 4 car. In fact, we have estimated that the substitution of older cars with new CNG-powered cars is on average 2.13 times more effective in CO_2 reduction than the substitution of Euro 0 with Euro 4 (between 1.8 and 2.7 times; Table 10).

Finally, we have estimated that the conversion of the 10% older cars in Italy to methane could decrease CO_2 emission by 302.54 tons per km (Table 11). The relevance of such reduction is huge; assuming each car travels on an average 12,250 km per year as reported by Automobile Club d'Italia (ACI, 2008) the overall CO_2 reduction will be 3,781,550 tons, which is 28.6% of the total CO_2 reduction (13,200,000 tons) that the EU Commission expects Italy to meet in order to bring Europe in compliance with Kyoto standards by 2012.

Table 8 CO_2 emissions of Italian circulating fleet by class of displacement, fuel and Euro standard

		Class of displacement			*Fleet weighted average*[12]		*Methane weighted average*	
		< 1,400 cc	*1,400–2,000*	*> 2,000 cc*	*(g/Km)*	*index*	*(g/Km)*	*index*
Euro 0	Gasoline	153	210	289	173	100.0	137	100.0
	Diesel	148	203	279				
	Methane bi-fuel	118	162	222				
Euro 1	Gasoline	150	206	284	178	102.9	141	103.0
	Diesel	160	220	303				
	Methane bi-fuel	116	159	219				
Euro 2	Gasoline	140	192	264	169	97.7	129	93.8
	Diesel	149	205	282				
	Methane bi-fuel	108	148	204				
Euro 3	Gasoline	117	161	221	154	89.0	112	81.9
	Diesel	125	172	236				
	Methane bi-fuel	90	124	171				
Euro 4	Gasoline	119	163	224	147	85.0	108	78.5
	Diesel	127	174	240				
	Methane bi-fuel	92	126	173				

Source: Elaboration on data CNR

Table 9 Italian circulating fleet by class of displacement, fuel and Euro standard (2008)

		Class of displacement			*Total*	
		<1,400 cc	*1,400–2,000*	*>2,000 cc*		
Euro 0	Gasoline	3,510,444	868,441	94,875	4,473,760	5,160,756
	Diesel	93,781	311,106	215,422	620,309	
	Methane bi-fuel	39,339	26,436	912	66,687	
Euro 1	Gasoline	1,783,541	751,441	34,172	2,569,154	3,022,028
	Diesel	1,194	297,697	112,938	411,829	
	Methane bi-fuel	17,871	22,789	385	41,045	
Euro 2	Gasoline	5,186,516	1,636,407	83,917	6,906,839	9,150,693
	Diesel	9,967	1,677,524	443,436	2,130,926	
	Methane bi-fuel	57,391	54,724	814	112,928	
Euro 3	Gasoline	3,014,895	633,311	83,226	3,731,432	8,387,490
	Diesel	559,161	3,262,238	770,672	4,592,070	
	Methane bi-fuel	23,485	40,047	456	63,988	
Euro 4	Gasoline	4,035,991	908,656	168,695	5,113,343	10,303,517
	Diesel	1,670,484	2,768,570	560,011	4,999,064	
	Methane bi-fuel	106,925	83,166	1,019	191,110	
					Total	36,024,484

Source: Elaboration on data from CNR

Table 10 CO_2 reduction by substitution and 'methanisation' (g/km)

	Euro 0–Euro 4 substitution		*Euro 0 'methanisation'*	
Class of displacement	*Gasoline*	*Diesel*	*Gasoline*	*Diesel*
<1,400 cc	34	21	61	56
1,400–2,000 cc	47	29	84	77
>2000 cc	65	40	116	106

Table 11 CO_2 reduction by substituting the oldest Italian cars with CNG ones

	Number of cars	*Class of displacement*	*Standard*	*CO_2 reduction per unit (g/km)*	*Overall reduction (ton/km)*
	112,938	Diesel > 2,000	Euro 1	129.587	14.635
	94,875	Gasoline > 2,000	Euro 0	115.599	10.967
	34,172	Gasoline > 2,000	Euro 1	110.199	3.766
	215,422	Diesel > 2,000	Euro 0	106.063	22.848
	297,697	Diesel 1,400–2,000	Euro 1	94.245	28.057
	868,441	Gasoline 1,400–2,000	Euro 0	84.072	73.011
	751,441	Gasoline 1,400–2,000	Euro 1	80.145	60.224
	868,441	Gasoline 1,400–2,000	Euro 0	77.137	66.989
	1,194	Diesel <1,400	Euro 1	68.542	0.082
	358,903	Gasoline <1,400	Euro 0	61.143	21.944
Total	3,603,523	(10% of the Italian circulating parc)			*302.524*

4 The CNG advantages in cost, availability and distribution

Apart from the evident environmental benefit, CNG would secure also significant economic benefit, since this resource is:

a widely available

b replaceable by biogas, that is a renewable source of energy

c less costly

d easier to transport distribute than conventional fuels.

Natural gas reserves are by far more spatially extended than oil reserves. The proven reserves of NG in 2009 are estimated at 177 trillion cubic metres, compared with a worldwide consumption that in 2005 has been 2.95 trillion cubic metres and that is expected to rise up to 4.32 trillion cubic metres by 2030[13]. Moreover the geographical distribution of NG is more balanced than that of oil (Table 12 and Table 13), and the refining process of natural gas is easier and less costly in terms of energy consumed. CNG can then be distributed by pipelines or by gas carrier ships[14], which are already widely used in Spain and being developed in other countries, like Italy that although already crossed by pipelines aims in this way to diversify supplies.

Recent technological advances in this area allow NG to be transported safely and efficiently worldwide. It is noteworthy that new technologies have liquefaction capacity significantly greater than that of previous generation systems; moreover, new liquid natural gas (LNG) tankers are almost twice in tonnage with respect to carriers available only two years ago. This allows to reduce transportation costs to such an extent that gas tankers have now become competitive with the construction of new pipelines, particularly for distances greater than 4,000 km.

According to various sources (Exxon, 2009; BP global website), in 2006 the global trade flows of LNG was around 150 billion cubic metres per annum, equivalent to 5% of total NG trade. The share of this transport is expected to raise up to 15% of global NG trade, equivalent to 720 billion cubic metres (BP statistical review) while costs per unit of the overall supply-chain will continue to decrease. Supplies will mainly come from the Middle East, Africa and Australia and will be consumed primarily in North America, Europe and Asia Pacific. This structural advantages are expected to determine effect on pump-price and in fact even now there is a significant price disparity between methane and both gasoline and diesel. Table 14 shows fuel prices in February 2009 in European Countries.

Of course, the methane pump price is affected by four main factors: the proximity to the extraction locations, the natural gas purity and the degree of methane content, the structure of the distribution market and the fiscal burden. For instance, in Russia, who is the world first methane supplier, the pump price is very low, equal to Euros 0.22 per kg, while premium gasoline (PG) and diesel are respectively at Euros 0.8 and 0.69 per litre. At equivalent energy with respect to on litre of PG, CNG cost is Euros 0.20 (0.6 euros less, –75%) and with respect to diesel is 0.23 (0.43 Euros less, –67%). Considering Western European countries as a whole, the pump price for all fuels increases significantly (on average: PG 1.174 €/lt; diesel 1.112 €/lt and CNG 0.656€/kg), but again the price of CNG at equivalent energy is definitely lower: the data for February 2009 show an average saving per km equal to 51.4% compared to PG and equal to 41.4% compared to diesel.[15]

Table 12 Geographic distribution of CNG worldwide proved reserves (2008)

North America	4.94%
Asia and Oceania	6.88%
Central and South America	4.26%
Europe	2.70%
Eurasia	31.88%
Middle East	41.44%
Africa	7.90%
Total	100.00%

Source: EIA (2008)

Table 13 Geographic distribution of CNG worldwide proved reserves: top 20 countries (2008)

Country	*Share*
Russia	26.86%
Iran	15.85%
Qatar	14.26%
Saudi Arabia 2	4.13%
United States 1	3.80%
United Arab Emirates	3.43%
Nigeria	2.94%
Venezuela	2.73%
Algeria	2.54%
Iraq	1.79%
Indonesia	1.69%
Turkmenistan	1.50%
Kazakhstan	1.36%
Malaysia	1.33%
Norway	1.31%
China	1.28%
Uzbekistan	1.04%
Kuwait 2	1.01%
Egypt	0.94%
Canada	0.93%
Total	90.73%

Source: EIA (2008)

Table 14 methane pump prices in European countries (2009)

February 2009	*Gasoline Premium €/lt*	*Gasoline Regular €/lt*	*Diesel €/lt*	*CNG €/kg*	*CNG equivalent gasoline (Gasoline = 1)*	*CNG equivalent diesel (Diesel = 1)*
Austria	1.24	1.23	1.29	0.89	0.80	0.91
Belgium	1.34	1.33	1.04	0.50	0.45	0.51
Finland	1.46	1.42	1.20	0.78	0.70	0.80
France	1.48	1.37	1.15	0.64	0.57	0.66
Germany	1.42	1.22	1.33	0.7	0.54	0.72
Iceland	1.47	1.39	1.41	0.9	0.81	0.92
Italy	1.48	1.39	1.34	0.68	0.64	0.71
Liechtenstein	0.95	0.92	1.09	0.86	0.75	0.82
Luxembourg	1.08	1.06	0.87	0.53	0.47	0.54
Netherlands	1.35	1.28	1.10	0.51	0.46	0.52
Norway	1.48	1.43	1.32	0.46	0.41	0.47
Portugal	1.13	1.07	1.01	0.55	0.49	0.56
Spain	0.97	0.87	0.9	0.57	0.44	0.49
Sweden	1.12	1.01	1.02	1.01	0.8	0.9
Switzerland	0.95	0.92	1.09	0.86	0.75	0.82
UK	1.04	1.00	1.16	0.71	0.63	0.73
Average W.E.	1.174	1.112	1.078	0.656	0.571	0.652
Belarus	0.69	0.55	0.55	0.27	0.24	0.28
Bulgaria	0.92	0.86	0.87	0.55	0.52	0.59
Bosnia and Herzeg	0.81	0.64	0.74	0.25	0.22	0.26
Croatia	0.84	0.83	0.86	0.34	0.3	0.35
Czech Republic	1.24	-	1.28	0.64	0.57	0.66
Latvia	-	0.79	0.82	0.23	0.21	0.24
Moldova	-	0.5	0.43	0.18	0.16	0.18
Poland	0.77	0.79	0.74	0.5	0.45	0.51
Russia	0.8	0.69	0.7	0.22	0.2	0.23
Slovakia	1.02	0.98	1.08	0.79	0.71	0.81
Turkey	1.7	1.6	1.26	0.78	0.68	0.76
Ukraine	0.44	0.4	0.4	0.15	0.13	0.15
Average E.E.	0.846	0.722	0.811	0.390	0.366	0.418
Average Europe	1.053	0.959	0.967	0.546	0.486	0.555

Source: The GVR

This means, i.e., that in case of an yearly travelling of 20,000 km with a ‘D’ segment car consuming eight litres per 100 km, the average yearly saving is about € 900 compared to gasoline engine and about € 740 compared to diesel. Thus, the additional cost of methane system installation in the gasoline engine would be paid back in two years or little more; instead, diesel engine has a higher initial price more or less comparable to the supplementary cost of CNG system and there is an immediate advantage. In brief, from the car's owner point of view, and apart from all environmental benefits, the purchase and use of a CNG-powered car is largely convenient in Western and Eastern Europe countries as well.

Both duties and oligopolistic market structure of gas distribution could have significant impact on final price. In this regard the study 'Well-To-Wheels Report' developed on behalf of EU claims that: "historically the price of natural gas has been loosely linked to that of crude oil, trading in Europe at around 60 to 80% of North Sea crude oil on an energy content basis" [European Commission (EC), (2007), p.96]. Moreover, according to a study by the Centre for Research on Energy and Environmental Economics and Policy IEFE (2007), the average excise duties in the EU would rather justify a higher pump price in Europe countries rather than in Italy, while it happens the contrary. The incidence of excise on fuels in the EU is on average the values reported in Table 15.

Table 15 Average excise duties in the EU (2006)

	€/GJ (HHV)
Unleaded gasoline	13,52692
Gas oil	9,196429
LPG	3,268696
Natural gas	2,018000

Source: IEFE (2007)

Table 16 Natural gas price in the USA supply chain (2008)

	\$ per m³	*\$ per kg (1)*		
	Average 2008	*Average*	*Min*	*Max*
Wellhead price	0.285	0.205	0.221	0.190
Imports	0.334	0240	0.259	0.222
Pipeline imports	0.331	0.238	0.256	0.220
Liquefied natural gas imports	0.365	0.263	0.283	0.243
US exports	0.336	0.242	0.260	0.224
US pipeline exports	0.341	0.246	0.264	0.227
Liquefied natural gas exports	0.260	0.187	0.201	0.173
City gate price	0.337	0.243	0.261	0.224
Delivered to residential consumers	0.546	0.393	0.423	0.364
Sold to commercial consumers	0.445	0.320	0.344	0.296
Industrial price	0.339	0.244	0.262	0.226
Natural gas electric power price	0.333	0.240	0.258	0.222

Notes: 1 Data from EIA are in dollars per cubic metre; the price per kg depends on the NG content of methane and on pressure and density of local distribution. Here the price per kg has been calculated with respect to cubic metre with a coefficient 0.72 ± 7.5%, under most common conditions (0°C, 1 atm).

Source: elab. from EIA

In this sense, it might be interesting to compare the detailed data provided by the Energy Information Administration (EIA), the official US energy authority about the prices along the natural gas supply chain to various retails network, assuming there are no specific peculiarities that might cause the US export price to diverge significantly from other exporters, it seems evident that the average European pump price of methane is definitely above its industrial cost (Table 16).

5 The demand of CNG vehicles

The share of CNG vehicles (CNGV) in different countries is very differentiated. There are countries where CNGV are the majority and others in which this fuel system is virtually absent. According to statistics reported by the journals *The GVR*, *Prensa Vehicular* and *Asian NGV Communications*, specialised in topics related to the CNG vehicles, at the end of 2008 the circulating fleet of CNGV was composed by almost 10 million units, about 1.2% of the total worldwide fleet (Table 17). The majority of these vehicles are composed by cars or light commercial vehicles, but also the number of medium-commercial vehicles (medium duty) and heavy (high duty); including buses, have a considerable role.[16]

Table 17 World CNG vehicle total registrations and refuelling stations – 2008

Country	*CNG vehicles*				*Refuelling stations*		
	Cars-LDV	*MD/HDV*	*Others*	*Total*	*Public*	*Private*	*Total*
Pakistan	1,949,960	40	50,000	2,000,000	2,600	-	2,600
Argentina	-	-	-	1,750,339	-	-	1,800
Brazil	-	-	-	1,588,331	-	-	1,699
Iran	1,209,381	6,212	-	1,215,593	705	61	766
Italy	576,500	3,500	-	580,000	630	70	700
India	315,200	12,715	493,957	821,872	319	6	325
China	212,000	104,500	1,100	336,500	844	416	1,260
Colombia				280,638	-	-	437
Bangladesh	117,229	11,588	51,183	180,000	290	6	296
Ukraine	7,000	60,000	53,000	120,000	204	20	224
Thailandia	103,294	22,768	1,673	127,735	278	25	303
Armenia	69,971	29,457	1,924	101,352	9	205	214
USA	-	-	-	115,000	-	-	816
Bolivia	-	-	-	99,657	-	-	123
Russia	18,000	43,000	34,000	95,000	199	25	224
Total 15 paesi	-	-	-	9,412,017	-	-	11,787
World total	-	-	-	9,942,883	-	-	14,339

Source: The GNV, Prensa Vehicular, Asian NGV Communications

As far the Newly Industrialised Countries (NICs), the presence of these vehicles is affected mainly by the availability of natural gas of good quality, free of sulphur and other impurities that lower the quality of gas and must be removed through filtering operations. For the countries with internal reserves of methane the pump cost is very convenient, in comparison to other fuels even if the country is not only producer but also refiner of gasoline and diesel fuel.

Moreover, a crucial role in the development of a CNG powered fleet is the availability of an adequate network of methane filling stations. It is no coincidence that the first four countries in the world fleet are also equipped with an extensive network of distribution points such as in Pakistan, Argentina, Brazil and Iran. Furthermore, in these countries the average pump price of CNG is extremely convenient. Consider that the cost compared to that of gasoline for the same energy output varies from a minimum of 12% in Iran to maximum of 50% in Brazil.

In Europe, the diffusion of methane powered vehicle is generally low, while as for the Heavy Duty vehicles and buses it much higher than other areas. Table 18 shows that the methane fleet is relevant only in Italy and some Eastern countries. Among the countries with high motorisation only Germany is about to exceed the threshold of 100,000 CNG powered units (580,000 in Italy). However, it emerges a growing interest by consumers and public administrations in several European countries to CNG vehicles. This trend has been further enhanced by the international economic crisis that has pushed the major European countries to promote a policy to support demand through incentives for car scrapping. Such incentives have promoted not only the sale of small cars but also cars powered by LPG and CNG. This happened mainly in Germany, France and Italy in favour of dual fuel cars (gasoline and LPG or gasoline and CNG).

Table 18 Europe CNG vehicles total registrations and refuelling stations (2008)

Country	*CNG vehicles*				*Refuelling stations*		
	Cars-LDV	*MD/HDV*	*Others*	*Total*	*Public*	*Private*	*Total*
Italy	576,500	3,500	-	580,000	630	70	700
Ukraine	7,000	60,000	53,000	120,000	204	20	224
Armenia	69,971	29,457	1,924	101,352	9	205	214
Russia	18,000	43,000	34,000	95,000	199	25	224
Germany	50,620	13,334	490	64,454	804	-	804
Bulgaria	60,000	220	35	60,255	1	69	70
Sweden	14,278	1,196	-	15,474	90	28	118
France	7,500	2,650	-	10,150	15	110	125
Poland	3,500	350	5,000	8,850	25	6	31
Switzerland	6,500	220	100	6,820	104	2	106
Total	813,869	153,927	94,549	1,062,355	2,081	535	2,616

Source: The GNR

Italy is for sure the market where the growth of demand for gasoline cars and CNG has been more dynamic. The share of registrations of such cars has risen from 1% in 2006 to 3.22% in 2008 and in the first nine months of 2009 has reached the share of 6%, which means more than 96,000 units overall. The growth has been even stronger for LPG-powered cars, which can benefit from a much more extensive distribution network than methane-powered ones. Their share raised up to 13.2% in the first nine months of 2009, that is almost 213,000 units. According to UNRAE, the joint effect of demand orientation towards smaller cars and the increase in CNG and LPG powered-cars have caused the average CO_2 emissions of new cars from 145 to 137.6 g/km. This is a very convincing signal about the opportunities offered by natural gas. Opportunities that can be fully grasp only through a proper development of the distribution network.

6 An optimal field of application for CNG technology: urban fleets

The market in which gas vehicles play a major role is the urban transport of goods and people. In big cities traffic has become extremely chaotic, while the levels of noise and harmful emissions and PM pose a serious threat to the health of population. Hence, there is an interest towards driving vehicles which may reduce the levels of pollution and emissions of green house gases.

Among various cases of use of CNG for heavy duty vehicles, the garbage collection in Madrid is particularly interesting (NGVA Europe, 2009), since it involves a huge fleet of CNG trucks.

Urban garbage collection in most Spanish cities is carried out at night. This makes it particularly sensitive to noise production, which derives from two sources: vehicle engine and loading and compacting operations.

In the early 90s Madrid Municipality defined as a priority a severe reduction in exhaust emissions of the vehicles carrying out the municipal services: passenger transport, cleaning services, waste collection and other. The goal was to reduce these emissions much more than the legal homologation limits expected for the near future. Moreover, Madrid Municipal Policy aimed at becoming the front-runner of innovative and alternative technologies regarding urban transport fuels and tractions.

Partner of the initiative here described were Iveco (previously Pegaso), FCC and Gas Natural S.A. Iveco, a company producing commercial vehicles controlled by Fiat, is long specialised in this type of offer. In 2008 more than 5,000 vehicles manufactured by Iveco were in operation in more than 80 cities across continents. These vehicles, equipped with a special engine and using exclusively CNG as fuel, had run for over 840 million km as a whole, giving a significant contribution to improving the degree of liveability in cities and demonstrating a strong reliability.

FCC (Fomento de Construcciones y Contratas) is the company that is providing this service to the Madrid Municipality, having won the majority of the consecutive tenders in the last 20 years. FCC has always been a company looking for the most modern, efficient and sophisticated equipments in order to provide the best service, which are regarded as their competitive advantage.

Gas Natural S.A. is the major Spanish gas company.

The first two trucks were completed and put in service in 1994. They were the first ever CNG trucks to run in Spain. After a four years period of intensive tests on all aspects related to this new technology (test on the two prototypes, on the filling station, on driver acceptance, maintenance learning and mechanics training), the conclusions drawn by FCC and Municipality of Madrid were very positive towards the new CNG technology trucks.

In the year 2000, a total of 40 CNG trucks were put into service, together with a dedicated FCC fleet depot that had been converted to a CNG filling station and shop-floor adaptations for new trucks. The experience of these 40 units running in 2000 was mainly to demonstrate that their performance regarding operational times, driver interchange ability, serviceability and maintenance downtimes were equivalent to the diesel units with the same mechanical configuration. At the same time, the total absence of black smoke, much lower gaseous emissions and reduced noise levels were highly appreciated by the neighbourhood of the areas where these CNG trucks operated.

Another major advantage, achieved with this first 40 truck fleet, was the fuel cost comparison with diesel, observing a significant saving that paid back in a few years the extra cost of acquisition of CNG trucks. Again the results were encouraging and the decisions from both, Madrid Municipality and FCC, were that in all subsequent tenders the whole fleet would be renewed with CNG trucks. In 2003 FCC bought 337 new IVECO CNG trucks.

The main economic data related to this experience are as follows:

- the fuel bill reduced by around 30% compared to diesel operated trucks
- total operating costs during the complete truck life, including all the investments for the gas compression station and extra costs towards trucks chassis, were still some 15% better than in diesel.

The positive experience in Madrid, in such big scale, has led FCC to assess if the CNG trucks are stamps of competitive advantages to be used in most of their upcoming tenders in Spain. Presently in Spain, FCC has put over 800 CNG trucks into operations in ten cities, thus becoming the private company with the biggest CNG truck fleet in Europe.

The case of the Municipality of Madrid is further interesting considering the fact that it has also activated a system to convert waste into the production of biomethane to be used in the refilling of the CNG fleet. It is important to note that at the moment the treatment processing capacity is limited to 25% of the waste produced by the city of Madrid, but this plant, currently the largest of its kind in Europe, is already able to feed a thousand trucks.

7 New technological frontiers of the CNG

The interest in developing the demand for methane powered vehicle and the corresponding industrial sector also stems from the fact that the technology associated with this kind of engine is able to develop further, producing interesting innovations from economic, productive and ecological points of view.

The first aspect concerns the spread of CNG over the next gasoline engine. The search for engines more economical and less polluting is prompting the automotive industry toward smaller displacement, but having requisite power and torque required by the customer. This requirement will be satisfied with the design of turbocharged engines that will then need CNG kit compatible with new generation engines. This step has already been achieved by the CNG industry and will see the first commercial production in 2009. This step assumes an important meaning because the new supercharged engines will provide the required fun to drive with the conversion to CNG. Thanks to its high knocking resistance, natural gas is the ideal fuel to use in the new, downsized and turbocharged engine platforms, where boosting is mandatory to realise low-end torque associated with a better fuel economy and a reduction of CO2 and other pollutants. Moreover, if the distribution of natural gas will grow adequately in order to make cars powered exclusively by CNG, it will be possible to exploit the best features of natural gas (octane) to raise the compression engine and achieve higher specific power.

Further improvements are also expected by the use of the Multiair®, a new technology patented by Fiat Group Automobiles. Experimental activities carried out on a 4 cyl. middle size engine have confirmed the high potentials coming from the use of natural gas on a turbocharged engine, capable of delivering 20 bar BMEP at less than 2000 rpm to increase the 'fun to drive' behaviour with an overall efficiency of more than 35%. Maximum specific power output target of 100 HP/litre was obtained under lean burn conditions at 5000 rpm thanks to the use of a variable geometry turbine group, maintaining the fuel conversion efficiency close to 33% (Gerini A. et al, 2009).

Another important aspect is the production of biomethane, almost pure methane gas produced via different technologies from biomass lignocellulosic (straw and wood) matter, other crops, or organic waste. Biomethane is chemically more or less identical to natural gas and fully interchangeable with natural gas, thus, it does not need special equipment. Biomethane produced from waste offers a more favourable greenhouse gas balance than any other fuel (including hydrogen produced with renewable power). In some cases (e.g., gas produced from manure), it is not only CO_2 neutral, but actually reduces overall GHG impact due to avoided natural leakages of methane, ammonia and N_2O (Ahlvik and Brandberg, 2001). This solution is especially advantageous when the place of production of biomethane is near to the filling stations. And this is precisely the case of plants for production of methane produced from biomass in Sweden since the 90s where some 25 plants are in operation today, and many more are planned. In Sweden biomethane now accounts for more than 50% of all methane used in vehicles.

Switzerland followed the Swedish initiative in 1998 and biomethane now accounts for some 30/40% of all methane used in vehicles. In France, the city of Lille operates a fleet of more than 300 NG buses where biomethane makes up 50% of the fuel used. Both Germany and Austria have introduced programmes this year ensuring that by 2020 biomethane shall account for 20% of all methane used in vehicles. In 2010, methane will account for a market share of 2% of the Swedish road fuels and 50% of this supply will arrive from biomethane[17]. In the 2030 scenario, biomass could provide a contribution of approximately 15%–16% of energy base in the European Union (Gerini et al., 2009).

Another important development that reinforces the use of natural gas in transport is the mixing of hydrogen with CNG. If hydrogen becomes available at competitive prices, then it would be immediately possible to use a mix of CNG (70%) and hydrogen (30%) using current engine technology. The advantage would be a further reduction of CO^2 emissions, but probably the most interesting aspect comes from the fact that this type of change would trigger the conditions for a broader use of hydrogen. In fact, the diffusion of this gas for transport suffers the same vicious circle already indicated for the CNG. An inadequate distribution network does not promote the use of hydrogen powered vehicles and in turn this prevents the expansion of the network. The use of a CNG-hydrogen mixture would be the first step to create the conditions for a wider application of hydrogen and would facilitate the process of diffusion of the network.

Finally, a further development is noteworthy to mention related to the use of methane in its liquid state. This fuel, LNG, has the considerable advantage to offer a much higher range with the same size of the cylinder, while maintaining the economic and ecological benefits of CNG. LNG would thus be a solution particularly interesting for heavy duty vehicles. The technologies which are necessary to implement LNG vehicles have already been acquired; once again, the problem stems from the proximity of the points of supply which in the case of LNG is a proximity to a re-gasification plant that receives the liquid methane from gas carriers ships that could directly supply the vehicles, thus, jumping a double process of transformation from liquid to gas and then gas to liquid.

In Europe, the most emblematic of this opportunity is the network of seven regasification centres located in the Iberian Peninsula, in addition to those operating in Marseilles in France and Genoa and Rovigo in Italy. There is therefore an opportunity to create a broad corridor from the Iberian Peninsula to Italy for the organisation of a heavy transport LNG-power.

8 Policy implications

The research carried out shows that there are many economic and ecological benefits arising from an expansion of the fleet fuelled with CNG. Benefits that should further increase over time, both as a result of technological improvements associated with investments in technology resulting from a greater diffusion of this type of vehicle and as a transition towards a mix of CNG with hydrogen and towards biogas.

The use of CNG is highly recommended for fleets of heavy duty vehicles and buses operating in urban areas. The growth of CNG powered vehicle appears definitely connected to the availability of CNG refilling stations. A policy of expansion of this network can be easily implemented, without excessively higher costs, in all countries that are crossed by CNG pipeline. For countries that do not have such infrastructure, it is possible to stimulate the creation of plants producing biomethane from biomass, using technologies and experiences that are already working and reliable, such as those pertaining to the case of the Spanish company FCC, and as those long experienced installations in Sweden and Switzerland.

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Notes

1 In fact, water vapour is the greenhouse gas most present in the atmosphere, but its impact on global warming is minor since it does not stay in the atmosphere for long time and its concentration, although constant on a global basis, changes very rapidly in specific areas. On the contrary, CO_2 remains in the atmosphere 50–100 years and build-up time after time. Other gases have a warming potential which is tens or even hundreds of times bigger than CO_2, but the actual contribution of these gases is not relevant due to their very low presence in the atmosphere. See: IPCC.

2 In this paper we call the methane also 'natural gas' and we use the two expressions as synonym, although the natural gas is in fact a mixture of gases extracted from natural fossil deposits that contains variable percentage of methane (from 80% to 97%–98%) plus other elements. This gas is different from the so called 'biogas', which is in fact a family of different kind of gases (mainly containing methane and CO_2) that are derived from the biological breakdown (anaerobic fermentation) of organic matter and that can be utilised as fuel as well.

3 That is: the ratio between the energy obtained by one unit of the fuel and the energy which is necessary to obtain that unit along the whole chain, from production to commercialisation.

4 As for the general sustainability of electric motorisation the 'well-to-wheel' supply-chain has to be taken into consideration. Specifically, the development of electric fleets actually reduce the overall impact on greenhouse gases if the electricity utilised in re-charging comes from renewable sources (sun, wind, hydroelectric) and such energy represents a surplus with respect with the average need of electricity (e.g., dedicated photovoltaic structures, night-recharging, etc).

5 To compare the costs of electricity with conventional fuel one should include the depreciation of batteries, but this is an estimate made complex by the fact that the actual battery life varies greatly according to type of use of the car. If the car owners could replace batteries in fuel stations (instead of charging them on their own each time they run out of energy), there would be two benefits:

a the cost of batteries for the final user would be a rental instead of a major initial cost

b in this way recharging would be much faster and the problem of short-range autonomy typical of electric cars would be overcome.

6 The calorific value (or heat of combustion) measures the energy that becomes available when a fuel is burned; it provides the basis for calculating the thermal efficiency of an engine using that fuel. Energy content can be expressed in Mega-joules per kilogram (MJ/kg) or per litre (MJ/l). For that one cubic metre of methane is equivalent to about 1.1 litres of petrol and one kilogram of methane is equivalent to about 1.5 litres of petrol. See Ahlvik and Brandberg (2001).

7 The fuel's knock resistance in spark-ignition internal combustion engines is expressed by the Research Octane Number (RON). The maximum allowable compression ratio of an engine, and hence its efficiency, depends on the knock resistance of the fuel, since a fuel with a too low RON will knock at high loads. Thus, the higher the octane number, the more knock-resistance and the higher the efficiency of the engine.

8 Average values on New European Driving Cycle (NEDC).

9 On the other hand, since methane and natural gas in itself produce a greenhouse effect that is estimated 20/23 times greater than CO_2, a relevant issue is the management of the whole cycle of NG in relation to the losses occurring during extraction and transport through pipeline; such losses are estimated between 0.2 and 0.7%. In this regard, NG total CO_2 emission (cycle and fuel) are likely to be inferior to those of gasoline and Diesel (Onufrio, 2005; JRC, 2006), but the positive ratio depends on the source of the NG and on the supply path, which is also called 'well-to-wheel' (WTW).

10 While we are writing this article the share of Euro 5 cars in the Italian fleet is still very low.

11 Indeed, in the Italian circulating fleet are already present 450,000 bi-fuel (gasoline + CNG) cars. These cars have not been taken into account to simplify the overall example. In fact, in our simulation we assume to increase the existing CNG fleet eight times. At the current rate of growth of CNG cars (> 30% per year including OEM installations and after market installations), and assuming a contemporary expansion of the network of CNG filling station, the goal of 10% could be reached in 2015, with a bigger probability if the cost difference between CNG and conventional fuels increase.

12 Data in Table 8 are referred to actual emissions of circulating fleet and they are affected by the fleet composition, specifically by the average displacement.

13 EIA Statistics are provided in cubic feet (1 cubic metre = 35.314667 cubic feet; 1 metric ton = 48,700 cubic feet); according to EIA, the US Energy Information Administration, the worldwide total natural gas consumption in 2005 has been 104 trillion cubic feet in 2005 and will rise up to 158 trillion cubic feet in 2030 (EIA, 2008).

14 The system of supply through gas ships requires a transformer station of the CNG in LNG at the port in the producing country. The passage of the gas in liquid form by cooling to –162°C reduces the volume of 600 times and makes it feasible transport by ship. In the destination

harbour, LNG is heated and returned to its gaseous state, with a procedure which is called ‘regasification’ and that give the opportunity of an additional energy recovery during gas heating and expansion, thus improving the energy balance of the overall process.

15 Moreover, one must consider that the comparison on prices taken as reference (February 2009) is relatively disadvantageous to the CNG, since it refers to a period in which fuel prices dropped while methane price remain more constant. In fact, the time gap between the drop in crude oil price and the adjustment is faster for gasoline and diesel than it is for the CNG. Thus, in February both conventional fuels already encountered a fall in prices, after peaking in July 2008, while methane price will probably be lower in May 2009.

16 In the table, 22 the class of vehicles ‘other’ refers to vehicles that are not easily classifiable into the two categories, LD and MD&HD since are vehicles used for special duties or belong to heterogeneous fleets of vehicles (off-road, minibuses, etc.).

17 Persson et al. (2006), presents a number of cases of production of biogas for motor fuel, and a census of the most significant of biogas plants in the world.