Energy Policy 62 (2013) 503–512

Contents lists available at ScienceDirect

Energy Policy

journal homepage: www.elsevier.com/locate/enpol

LNG as vehicle fuel and the problem of supply: The Italian case study

A. Arteconi [a,*], F. Polonara [b]

[a] Università degli Studi eCampus, via Isimbardi 10, Novedrate (CO) 22060, Italy
[b] Università Politecnica delle Marche, Dipartimento di Ingegneria Industriale e Scienze Matematiche, via Brecce Bianche 1, Ancona 60131, Italy

HIGHLIGHTS

• LNG potential as vehicles fuel is analysed.
• A SWOT analysis for LNG introduction in the Italian market is presented.
• An economic comparison of different supply options is performed.
• Possible micro-scale liquefaction technologies are evaluated.

ARTICLE INFO

Article history:
Received 6 March 2013
Accepted 5 August 2013
Available online 29 August 2013

Keywords:
LNG
Alternative fuels
Supply chain

ABSTRACT

The transport sector represents a major item on the global balance of greenhouse gas (GHG) emissions. Natural gas is considered the alternative fuel that, in the short-medium term, can best substitute conventional fuels in order to reduce their environmental impact, because it is readily available at a competitive price, using technologies already in widespread use. It can be used as compressed gas (CNG) or in the liquid phase (LNG), being the former more suitable for light vehicles, while the latter for heavy duty vehicles. The purpose of this paper is to outline the potential of LNG as vehicle fuel, showing positive and negative aspects related to its introduction and comparing the different supply options with reference to the Italian scenario, paying particular attention to the possibility of on site liquefaction. The analysis has highlighted that purchasing LNG at the regasification terminal is convenient up to a terminal distance of 2000 km from the refuelling station. The liquefaction on site, instead, asks for liquefaction efficiency higher than 70% and low natural gas price and, as liquefaction technology, the let-down plants at the pressure reduction points along the pipeline are the best option to compete with direct supply at the terminal.

1. Introduction

Nowadays there is a growing interest in renewable energy sources and more sensitivity towards environmental issues. The transport sector represents a major item on the global balance of greenhouse gas (GHG) emissions. In Europe (EU-27) the GHG emissions due to the transport sector amounted to about 20% of the total emissions in 2009 (EEA, 2011) and between 1990 and 2007 emissions from transport rose by 29%. This increase was observed for both passenger transport and freight transport, mainly due to growing transport demand, in particular freight transport increased share of road freight transport as opposed to other transport modes. In an attempt to contain this phenomenon, European policies are being implemented to reduce GHG emissions, e.g. by promoting transport by rail, producing passenger cars with more limited GHG emissions and promoting the use of biofuels or alternative fuels. The European Union's Green Paper specifies the need to substitute 20% of conventional fuel consumption with alternative fuels by the year 2020 (EC, 2001a).

In this context alternative fuels have assumed more and more importance and a lot of incentives have been introduced to support them. Natural gas (NG) is considered the alternative fuel that, in the short-medium term, can best substitute conventional fuels in order to reduce their environmental impact (EC, 2001b), because it is readily available at a competitive price, using technologies already in widespread use (Hekkert et al., 2005). It can be used as compressed gas (CNG, compressed natural gas) or in the liquid phase (LNG, liquefied natural gas). In small fuel tank sizes, which are suitable for small vehicles, CNG is generally more

Abbreviations: BOG, boil off gas; CAPEX, capital cost; CNG, compressed natural gas; COP, coefficient of performance; ECA, emission control area; GHG, greenhouse gas; *J–T*, Joule–Thomson; LCNG, liquefied/compressed natural gas; LNG, liquefied natural gas; MRC, mixed refrigerant cycle; NG, natural gas; NGV, natural gas vehicles; OPEX, operative costs; SWOT, strength, weakness, opportunity, threat

* Corresponding author. Tel.: +39 71 220 4437; fax: +39 71 220 4770.
E-mail addresses: a.arteconi@univpm.it, alessia.arteconi@uniecampus.it (A. Arteconi).

0301-4215/$ - see front matter © 2013 Elsevier Ltd. All rights reserved.
http://dx.doi.org/10.1016/j.enpol.2013.08.016

Table 1
Fuels properties.

Fuel	Temperature	Pressure	Density	Energy content[b]
	°C	MPa	kg m^{-3}	MJ kg^{-1}
CNG[a]	15	22	181.4	50
LNG[a]	−161.5	0.1013	422.4	50
Diesel	15	0.1013	848	42

[a] NG is considered 100% CH_4.
[b] Source: www.afdc.energy.gov.

appropriate because space and weight are not critical criteria. For heavy duty vehicles, particularly fleet vehicles, LNG becomes attractive because of reduced on-board weight and space requirements, due to its higher energy density. Thus LNG is typically the substitute for diesel fuel. In Table 1 CNG, LNG and diesel main properties are reported for comparison.

Main advantages of Natural Gas fuel are (Yeh, 2007): (i) environmental benefits for reducing local air pollution and GHG emissions, (ii) availability of natural gas resources and (iii) reduction of dependency on imported oil. In particular the reduced environmental impact has been the aspect that has been pushing the NG on the European market. In order to show such environmental benefits, a comparison among the well-to-wheel life cycle GHG emissions for CNG, LNG and Diesel has been performed (Arteconi et al., 2010a). It has been put into evidence that CNG reduces GHG emissions by 14% and LNG by 10% if compared with Diesel and the main GHG reduction is due to reduced emissions in the tank-to-wheel phase. Moreover CNG fuel cycle has lower emissions than LNG fuel cycle, because of the additional energy requested for natural gas liquefaction and shipping. Eventually the emissions are also connected with the supply option considered: for LNG shipped to the terminal the emissions reduction is higher than that for LNG liquefied on site (that is only 3% less than Diesel) (Arteconi et al., 2010b).

In fact, concerning the LNG value chain, it can be supplied to refuelling stations by two different sources: (i) purchased at regasification terminal or (ii) liquefied on site. Then vehicles can be refuelled at LNG refuelling stations, LNG is stored in cryogenics tanks on board and finally burnt in LNG-adapted engines. The technology for refuelling, storing and burning LNG is already available, the real bottle neck of this value chain is represented by the distribution phase, that is still difficult to fulfil in many countries.

The purpose of this paper is to outline the potential of LNG as vehicle fuel, showing positive and negative aspects related to its introduction and comparing the different supply options with reference to the Italian scenario, paying particular attention to the possibility of on site liquefaction.

2. LNG as vehicle fuel in the Italian scenario

LNG as vehicle fuel is already used in the US, China and Europe. The case of Italy is presented in this paper and discussed in the following sections. Main findings of the analysis showing strengths, weaknesses, threats and opportunities for the introduction of LNG as vehicle fuel in the Italian market are summarised in Fig. 1 and discussed in detail in the following sections.

2.1. The reference scenario

As already mentioned, LNG is the only choice for heavy duty trucks intended to do long distance, CNG being not valid because the required volume of CNG tanks is not compatible with the payload of the trucks. It is foreseen that LNG will cover about the 33% of the long distance road transport by 2035 (Lage, 2012).

In Italy the use of natural gas is well spread, thanks to the wide pipeline distribution. Italy has about 780,000 natural gas vehicles (NGVs), that is the 77% of the total number of NGVs in Europe, and the 30% of European natural gas refuelling stations (NGVA, 2011). Among the 860 Italian refuelling stations (that represent about the 4% of the total number of motor fuel stations in Italy (UP, 2012)), 2 are LCNG stations, where LNG is stored liquid, pumped and vaporised to be used as CNG. They represent the first attempt to introduce LNG in the automotive market. Surely the uptake of LNG as fuel can benefit from the important role of NG in Italy. At this aim Cryotrucks, an association of companies working in several fields, as automotive, storage, refuelling, was also established.

As far as the technology on board is concerned, it is mature and big companies of the automotive sector are developing their own trucks. Fiat Iveco, for example, launched its new LNG fuelled truck for applications carrying between 18 and 40 t.

2.2. The infrastructure and the supply options

The distribution for alternative fuels is always a critical issue. Natural gas pipelines are widely spread in a lot of Italian regions but NG refuelling infrastructures are still facing the challenge of achieving the optimum ratio between NG vehicles and refuelling stations. Refuelling station distance and waiting time for refuelling are critical aspects for the public acceptance of alternative fuels vehicles. Different surveys have analysed this point and they suggest that with a number of stations equal to 10–20% of conventional gasoline stations, refuelling is no longer seen as a major obstacle for the adoption of a NGV (Yeh, 2007). In order to overcome these barriers, a European project called GasHighWay (GHW, 2009) has been established, aiming at promoting the uptake of gaseous vehicle fuels, namely biomethane and CNG, and especially the realisation of a comprehensive network of filling stations for these fuels spanning Europe from the North, Finland and Sweden, to the South, Italy. Similarly, the Blue Corridor Project has the objective to establish transport corridors for heavy duty transport vehicles using liquid natural gas fuel instead of diesel, both because of its economic and environmental advantages. The Blue Corridor Project is included in the programmes of work of the United Nations Economic Commission for Europe Working Party on Gas and Inland Transport Committee (UNECE, 2003). In addition, recently the European Commission launched a clean fuel strategy, an ambitious package of measures to ensure the build-up of alternative fuel stations (LNG, CNG, LPG, Hydrogen, electric vehicles) across Europe with common standards for their design and use, recognising that “clean fuel is being held back by three main barriers: the high cost of vehicles, a low level of consumer acceptance, and the lack of recharging and refuelling stations”. It plans a grid of LNG refuelling stations for road transport every 400 km (EU, 2013).

LNG has also to overcome another issue rather than the spread of refuelling infrastructures, that is how to supply the refuelling stations. There are two possibilities for LNG supply: (i) to buy it at LNG terminals or (ii) to liquefy pipeline natural gas directly on site.

Regarding the first option, there are two working LNG terminals in Italy at present: the on-shore terminal in Panigaglia (North, West coast) and the off-shore gravity based terminal in Rovigo (North, East coast). Other 7 terminals are planned and waiting for permissions to be issued, but the authorisation process is not expected to be short. Moreover at the moment it is not possible to buy spot LNG cargos at the existing terminals, because all LNG is regasified and sent into the pipeline. The two existing LCNG refuelling stations in the North of Italy are forced to buy LNG at Barcelona terminal. It is the closest to Italy that sells LNG, but

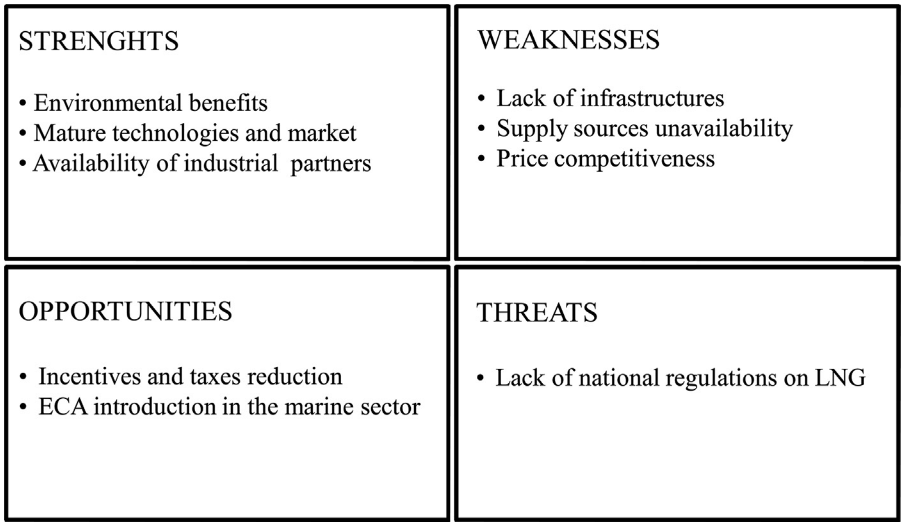

Fig. 1. Results of the SWOT analysis.

nevertheless it is about 800 km far away the border and considering transportation costs and boil-off gas (BOG) production during the delivery (gas formed from liquid evaporation due to heat gains), this scheme does not seem very economical, at least for the Southernmost regions.

The second option deals with the liquefaction on site of pipeline gas. This solution is attractive because the LNG can be ready available where there is a request and the widespread pipeline network allows to reach almost every place. The main issue of this option concerns the availability of small-scale liquefaction plants and the necessity to find the right trade-off between capital costs and energy efficiency for plants at this scale, as discussed later.

2.3. System of "incentives"

As several studies pointed out, the market introduction of alternative fuels depends on the actions of many stakeholders, like car industry, fuel companies and consumers (Janssen et al., 2006; Engerer and Horn, 2009; Suurs et al., 2010). Also Governments have a central role for promoting NGVs by regulating fuel taxes (Sterner, 2007) and introducing incentive-based instruments. In Italy a policy to promote NGVs was carried on in the last years and it helped the diffusion of CNG vehicles. It consisted in rebates to convert traditional engines in natural gas fuelled engines. Moreover natural gas used as vehicle fuel can benefit of a reduced taxation and it is foreseen that the same regulations will be implemented also for LNG. In fact a critical aspect for the introduction of a new fuel is its economy. Generally in most countries that have had a successful NGVs penetration the NG pump price is 40–60% below the gasoline price (Yeh, 2007), in terms of energy delivered, mainly due to reduced taxation. Surely the price difference between NG and conventional fuels is one of the most important factors in attracting users, together with the availability of a proper infrastructure. In Table 2 a breakdown of fuels costs in Italy is shown (MSE, 2012). Not being sold at present, the LNG retail price has been assumed as 60% of the energy equivalent Diesel quantity, assessed considering the different energy content of LNG (21 $\mathrm{MJ\,l^{-1}}$) and Diesel (35.8 $\mathrm{MJ\,l^{-1}}$). This baseline LNG price is meant to be the threshold value that could push customers to shift from Diesel to LNG.

Another positive contribution to the introduction of Government's help will come also from the European Union and the target of 20% share of alternative fuels by 2020.

Moreover, recently a new boost to consider LNG as fuel is connected with the new rules in the marine sector, where increasing oil prices and new legislation are driving the technology towards ways of reducing emissions. In fact the Mediterranean area is going to become an Emission Control Area (ECA), that means it will be subjected to more stringent requirements for fuel quality and emissions. Currently, Baltic Sea, North Sea and US coast are the only ECA in the world (US coasts became ECA in August 2012), while Mediterranean could become an ECA in 2015. Within ECA, ship owners need to switch to cleaner fuels (e.g. LNG) or to adopt alternative technologies (e.g. scrubber, after-treatments) to reduce emissions. The use of LNG has been evaluated as the best solution by the involved stakeholders. The LNG powered propulsion can allow to achieve the following pollutants reduction: CO_2—23%; NO_x—92%; SO_x—100%; Particulate—98 ÷ 100% (Andreola, 2012). Mainly it completely avoids SO_x emissions, because LNG does not contain sulphur, in accordance with ECA regulation that sets a 0.1% sulphur content as limit after 2015 (IMO, 2011). Therefore, considering the coast length in Italy and the economic relevance of shipping business, the introduction of the ECA in the Mediterranean area will contribute to build the necessary infrastructure for delivery LNG as fuel and solve the problem of LNG supply.

2.4. Laws and regulations

The main threat for the uptake of LNG is the lack of a national regulation both for LNG technology on board and for its storage and delivery in the refuelling stations. The Italian law D.Lgs 334/1999, that comes from the European Directive 96/82/EC on the control of major-accident hazards involving dangerous substances, is a general reference for safety regulations in LNG installations. To cover all the other issues, the reference is represented by international regulations as reported in Table 3.

Because of the absence of a national law, the request for permissions to build LNG facilities, such as LCNG or LNG refuelling stations, becomes very complicated. The main difficulty is due to the fact that the permission process is local, meaning that it depends on local authorities and local fire department. This aspect, together with the lack of information about the topic, does not help the build up of a standard procedure for the authorisation process that can be shared on the whole Country and repeated everywhere in the same way.

Table 2
Fuels cost breakdown (MSE, 2012).

Fuel	CNG		LNG		Diesel		Gasoline		LPG	
Baseline price	0.5506	€ m^{-3}	0.4947	€ l^{-1}	0.7941	€ l^{-1}	0.7184	€ l^{-1}	0.5819	€ l^{-1}
Tax	0.0033	€ m^{-3}	0.0021	€ l^{-1}	0.6174	€ l^{-1}	0.7280	€ l^{-1}	0.1472	€ l^{-1}
VAT (21%)	0.1163	€ m^{-3}	0.1043	€ l^{-1}	0.2964	€ l^{-1}	0.3038	€ l^{-1}	0.1531	€ l^{-1}
Retail Price	0.6703	€ m^{-3}	0.6011	€ l^{-1}	1.7079	€ l^{-1}	1.7502	€ l^{-1}	0.8822	€ l^{-1}
Normalised price	0.0192	€ MJ^{-1}	0.0286	€ MJ^{-1}	0.0477	€ MJ^{-1}	0.0541	€ MJ^{-1}	0.0347	€ MJ^{-1}

Table 3
International regulations on LNG.

Regulation name	Description
ISO 12991	Liquefied natural gas (LNG)—Tanks for on-board storage as a fuel for automotive vehicles
EN 1160	Installations and equipment for liquefied natural gas—General characteristics of liquefied natural gas
EN 13645	Installations and equipment for liquefied natural gas—Design of onshore installations with a storage capacity between 5 t and 200 t
EN 1473	Installation and equipment for liquefied natural gas—Design of onshore installations (larger installations)
NFPA 59A	Standard for the Production, Storage, and Handling of Liquefied Natural Gas (LNG)
NFPA 52	Vehicular Fuel Systems Code
ISO 12617	LNG connector (Draft International Standard in 2012)
ISO 12614	LNG vehicle onboard equipment (Draft International Standard in 2012)
ISO 16924	LNG station for fuelling vehicles (Committee Draft in 2012)

3. Comparison of different supply options

Considering the criticality of the LNG supply phase for the considered application, a comparison between the two possible scenarios (purchase at the regasification terminal and liquefaction on site) has been performed. The analysis refers to a sample LNG facility with a capacity of 10,000 l of LNG per day, suitable for a final user with a fleet of about 25 trucks.

The first scenario (Scenario 1) considers that LNG is bought at the regasification terminal, then it is transported to the final user by LNG tanker trucks, where it is stored in the dispenser of an LNG refuelling station and supplied to the vehicles. A 20,000 l tanker truck is used to deliver LNG to the refuelling station, so that 3 trips per week are necessary. At the refuelling station a storage of the same capacity as the tanker truck is available. The LNG is pumped from the truck to the storage and from the storage to the on board tanks.

In the second scenario (Scenario 2), instead, the LNG is produced with a small scale liquefaction plant that takes natural gas from the pipeline and sends the liquefied natural gas to the storage tank of the refuelling station. The plant efficiency is defined as the ratio between the produced LNG and the total natural gas entering into the liquefaction plant, considering that it is used also to fuel the liquefaction process. Thus an 80% of efficiency means that 80% of the natural gas becomes liquid and 20% is used as fuel in the process.

In Figs. 2 and 3 a schematic of the scenarios is shown, together with the cost breakdown along the supply chain. Values reported have been calculated with the following hypothesis.

For the first scenario (Fig. 2), the final LNG price depends on:

i. the LNG selling price at the terminal, that is 11.05 \$ MMBTU^{-1}, i.e. 0.17 € l^{-1} (FERC, 2012), and the terminal operator mark up;
ii. the transportation costs: the regasification terminal of Barcelona has been considered, that is about 800 km far away the Italian border, so that a distance of 900 km between the terminal and the LNG station has been assumed. For a conservative evaluation, the possibility of boil off formation in the storage tanks has been considered (0.05% of the stored volume per day), in fact, even if the gas can be recovered, it represents a loss in the LNG value chain (Chen et al., 2004; Querol et al., 2010).
iii. the refuelling station costs, that include capital costs (station amortisation) and operative costs (labour, maintenance, energy and boil off losses), plus a station operator mark up.

The final LNG baseline retail price (taxes and VAT excluded) has been assessed as 0.32 € l^{-1}.

In the second scenario (Fig. 3), instead, the LNG price depends on:

i. pipeline natural gas, that is 0.35 € m^{-3}, i.e. 0.21 € per litre of LNG (MSE, 2012);
ii. liquefaction costs, that include capital costs (plant amortisation) and operative costs (labour, maintenance, feedstock and energy, related to the plant efficiency), plus a plant operator mark up. The liquefaction plant located close to the refuelling station allows to recover and reliquefy BOG (Sayyaadi and Babaelahi, 2010);
iii. the refuelling station costs.

The obtained LNG baseline retail price is 0.44 € l^{-1} (taxes and VAT excluded).

These results show a better convenience of the first supply scenario, but they are dependent on the assumed hypothesis, for this reason a sensitivity analysis based on the most relevant parameters has been performed.

In Scenario 1 the LNG price depends mainly on the LNG selling price at the terminal and on the distance between the terminal and the station. Fig. 4a shows that even increasing the LNG price at the terminal by 50%, the LNG retail price is lower than the threshold (0.4947 € l^{-1} without taxes, see Table 2). Moreover, looking at the trend of the LNG terminal price, in the last two years it was pretty much constant at the present value, while in the past its value was similar to the US price, that is typically lower than 5 \$ MMBTU^{-1} (FERC, 2012), so it is not a major issue. Regarding the distance, instead, the LNG price is kept lower than the threshold up to 2000 km (Fig. 4b), so that only the Italian Southernmost regions are excluded by this supply option.

In Scenario 2 the LNG price is affected by the NG pipeline price and by the energy efficiency of the liquefaction plant, as it is shown in Fig. 5a and b respectively. In particular Fig. 5a shows that the liquefaction on site is interesting only for plant efficiency above 70%, otherwise the LNG price overcomes the considered

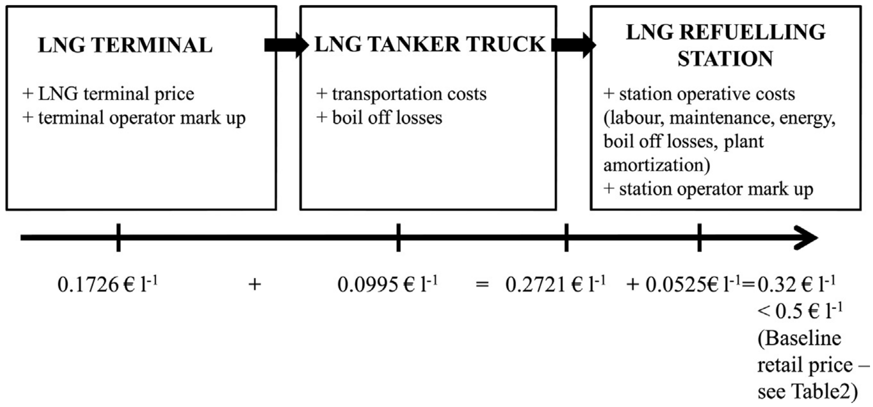

Fig. 2. Scenario 1: cost breakdown.

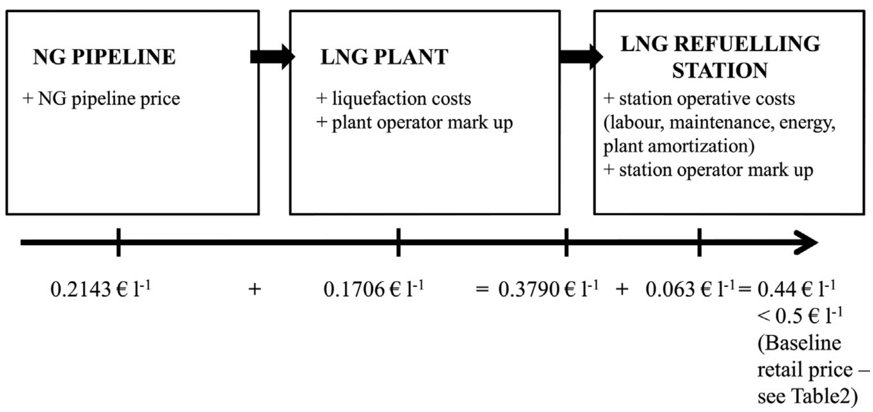

Fig. 3. Scenario 2: cost breakdown.

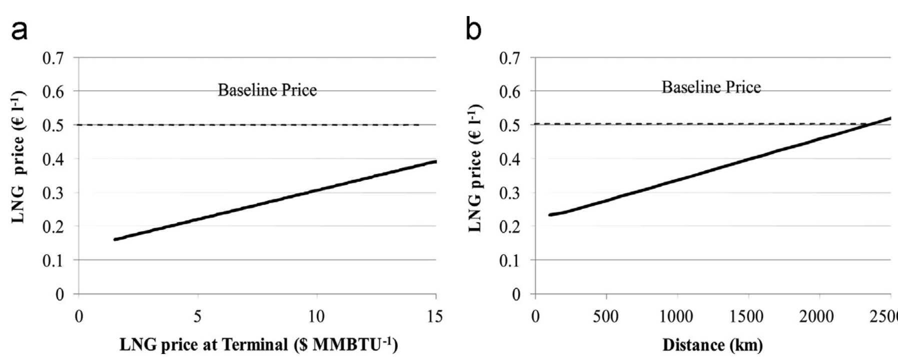

Fig. 4. Scenario 1: LNG baseline price trend varying the LNG selling price at the regasification terminal (a) and the distance between refuelling station and terminal (b) (Arteconi and Polonara, 2012).

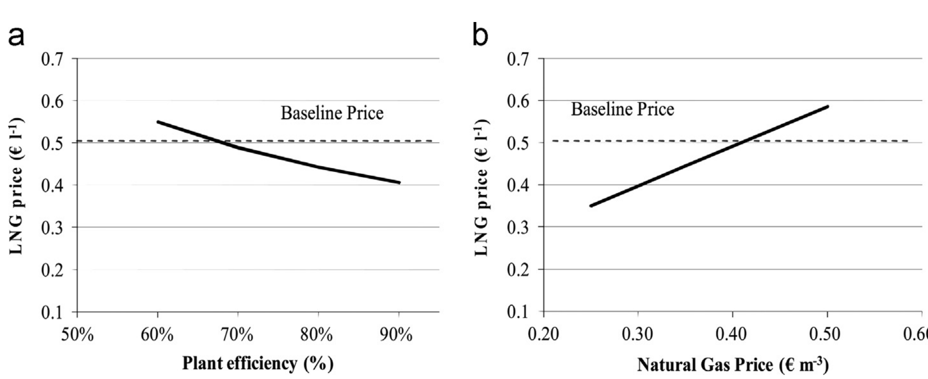

Fig. 5. Scenario 2: LNG baseline price trend varying the liquefaction plant efficiency (a) and natural gas pipeline price (b) (Arteconi and Polonara, 2012).

threshold. Much more influence is held by the pipeline price (Fig. 5b), that rises the LNG price of about 7% by a 10% increase, demonstrating the importance of the business model that regulates the supply option: a substantial economic advantage is foreseen if the natural gas Utility is involved in establishing this LNG supply chain, because it can profit by lower NG fares.

Eventually, the LNG threshold price ("Baseline price" in Figs. 4 and 5), assessed as explained previously in Section 2.3, is related to diesel price. Thus the more the diesel price increases, the more the substitute fuel LNG is economically viable and the price growth that conventional fuels have been experiencing lately can have a positive effect on the economy of this new fuel. Furthermore for sake of clarity, it is important to notice that LNG heavy duty vehicles typically use dual fuel engines. They are based upon diesel technology: the primary fuel is natural gas with diesel as a 'pilot' ignition source. When the vehicle is at full load performance, natural gas replaces diesel fuel up to a percentage of 80% or more. This aspect, together with possible taxation reduction or discounted prices on fuels for the fleet owners, should be taken into account for evaluating the actual convenience for the final user to shift to LNG.

4. NG liquefaction on site

Considering that in Italy LNG purchase at the terminal is not possible currently, in this section a special attention is paid to the supply option of the liquefaction on site and to those technologies

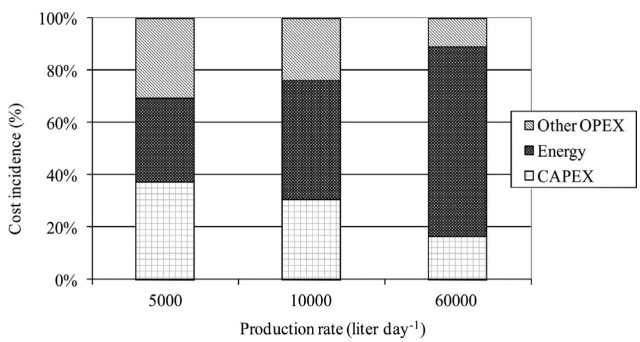

Fig. 6. Incidence of different costs on the total annual cost of an LNG plant (Arteconi et al., 2011).

that make it possible. For the application here considered, micro-scale plants are necessary. A micro-scale plant is a plant with a production rate lower than 60,000 l of LNG per day (about 0.01 mtpa, million ton per annum). At such a scale, finding the right trade-off between capital and operating costs has a key role. In particular, it is of paramount importance to keep the capital cost low with the reduction of the plant size, while when the production rate increases the energy cost becomes more consistent, so it is worth complicating the process in order to increase the energy efficiency. Fig. 6 represents the influence of capital costs (CAPEX) and operating costs (OPEX, divided in energy costs and other opex, feedstock costs are excluded) on the annual cost of an LNG plant (Arteconi et al., 2011). On the basis of the indications of Fig. 6, at the scale of 10,000 l per day, capital costs have about the same weight as operative costs (in order to give an order of magnitude of such costs: the capital investment is about 1.5 M€, while the energy costs are about 200 k€ per year), so only methane expansion liquefaction cycles are considered in this evaluation for their simplicity. The following sections are meant to study different liquefaction technologies in order to assess the different LNG production cost achievable.

4.1. Performance of the liquefaction technologies

The liquefaction technologies analysed, suitable for a 10,000 l per day plant for NG liquefaction on site, are Linde cycle (Fig. 7a) and Claude cycle (Fig. 7b) with and without pre-cooling (Walker, 1983). Moreover for the considered application of supplying LNG to refuelling stations also let-down plants are analysed (Fig. 7c). A let-down plant is built at pressure reduction points along the pipeline network so that it exploits the pressure drop necessary to send the gas from the transmission to the distribution pipelines. Prototype units are available in the US (Chrz and Emmer, 2003). The liquefaction cycles are compared on the basis of energy efficiency of each liquefier.

The thermodynamic analysis has been performed using the Peng–Robinson–Stryjek–Vera (PRSV) equation of state to calculate the thermodynamic properties of the substances (Stryjek and Vera, 1986). It has been assumed that the natural gas stream is composed of 100% methane, available at 25 °C and 0.1013 MPa. Liquefied natural gas produced is at −161.5 °C and 0.1013 MPa. A minimum approach temperature of 5 °C has been considered in the heat exchangers and compressor and expander have 75% of

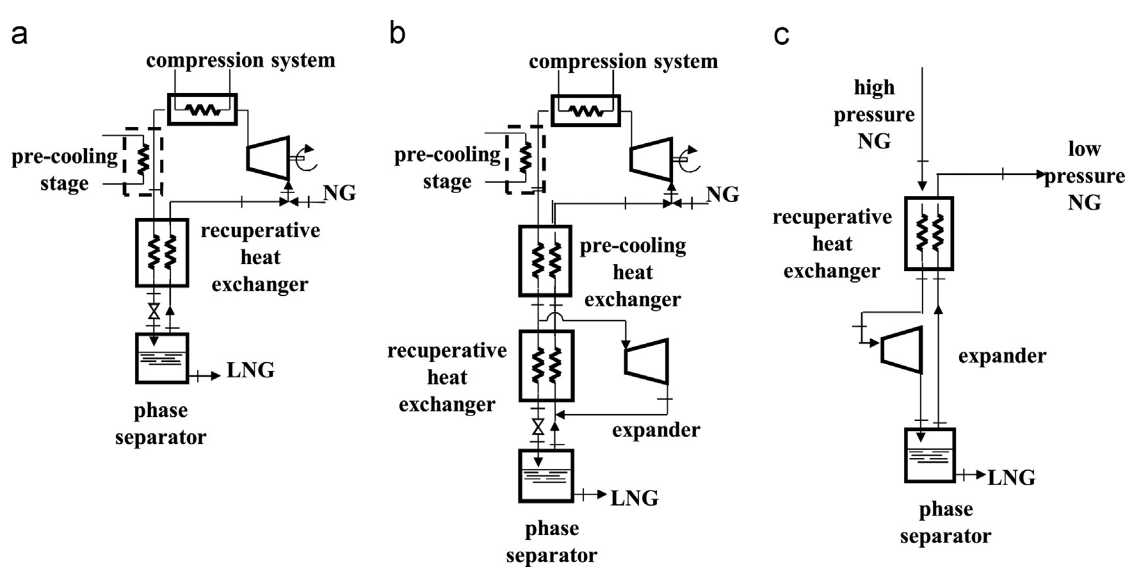

Fig. 7. Liquefaction processes: (a) Linde liquefaction cycle; (b) Claude liquefaction cycle; (c) Let-down plant (Arteconi et al., 2012).

isentropic efficiencies, pressure drops have been neglected. The analysis refers to an LNG facility with a capacity of 10,000 l of LNG per day. The purification process is not taken into account, because it is the same for all liquefaction cycles and depends on pipeline gas quality. Hypothesis and simplified schematics are justified by the purpose of comparing the different cycles rather than quantify the efficiency itself.

In the Linde cycle, natural gas is compressed with a multi-stage compressor to the maximum pressure of 20 MPa, the heat of compression is rejected through an external refrigerant (e.g. water), and then it goes across the recuperative heat exchanger where it is precooled and subsequently expanded in a Joule–Thomson (*J–T*) valve. The stream coming from the *J–T* valve contains a small fraction of liquid, that is the final product, while the remaining gas is sent back through the heat exchanger in order to cool down the incoming compressed gas. It is possible to add a pre-cooling heat exchanger before the main recuperative heat exchanger to improve the cycle performance. The necessary cooling load can be provided by a vapour compression chiller, that should be available off-the shelf not to complicate the plant configuration. Reasonably, for such a unit, the minimum temperature achievable is -30 °C with a coefficient of performance (COP) half of the ideal Carnot COP (COP=2).

In the Claude cycle it is possible to work at lower pressure than the previous case, thanks to the presence of the expander: part of the compressed gas is expanded in a turbine causing a decrease of the temperature and this low pressure gas is sent through the recuperative heat exchanger so to pre-cool the main stream. The latter then is sent to the *J–T* valve whose outlet stream contains a greater liquid fraction (LNG) than the Linde cycle. The maximum pressure used in calculation and assessed by means of optimisation methods is 5 MPa. The fraction of NG entering the turbine is 75% of the total gas stream. In this case the possibility to add a pre-cooling heat exchanger is not interesting, due to the very low improvement in the cycle performance.

The last system analysed is the let-down plant. In Italy the transmission pipeline has a pressure of about 7–8 MPa and it drops to 2.5 MPa going into the distribution network. A let-down plant does not need any compression phase because it takes the high pressure gas from the pipeline and expands it through a *J–T* valve or an expander down to the distribution pipeline pressure. The vapour fraction is first sent through the recuperative heat exchanger to precool the incoming gas and then into the distribution network, while the liquid fraction is the final product (LNG) that can be stored at said pressure or further expanded down to the necessary pressure.

In Table 4 main results of the energetic evaluation are reported. The net power ($\dot{W}_{net}$) has been assessed considering the power requested by the compressor plus the power requested by the chiller when the external pre-cooling is included and subtracting the power produced by the expander. The specific work has been expressed in term of the necessary energy (kW h) to produce 1 kg of LNG. Moreover, considering to fuel the plant only with natural gas, it has been assessed the amount of fuel necessary to produce said liquefaction energy with an energy conversion efficiency of 30%. In this way the specific work for liquefaction has been represented as the ratio between the produced LNG and the total natural gas entering into the liquefaction plant, considering also the gas used to fuel the liquefaction process (i.e. an 80% of efficiency means that 80% of the natural gas becomes liquid and 20% is used as fuel in the process, as already mentioned in an earlier section of the present paper). As previously stated the pre-cooling phase has a positive impact on the Linde cycle performance, making it comparable with that of the Claude cycle, while its effect on the Claude cycle is negligible. The let-down plant, instead, does not need any external power nevertheless producing power by means of the gas expansion trough the turbine.

For sake of completeness, other liquefaction technologies that can be considered at small-scale are: mixed refrigerant cycle (MRC) and liquefaction by means of liquid nitrogen.

The former is a process widely used also in the base load liquefaction plants and its performance depends on the mixture of refrigerants used, that typically contains hydrocarbons and/or nitrogen in different percentages. The mixture is first compressed, then it is cooled and the heavier hydrocarbons are liquefied. The liquid phase is separated from the gaseous phase and it undergoes to expansion processes, typically through *J–T* valves,

Table 5
Results of the economic evaluation of the different liquefaction cycles.

	Linde	Linde+precooling	Claude	Let-down
Capital cost (1000 €)	1000	1200	1500	1000
Annual operating cost (1000 €)	1281	1107	1090	884
Amortisation (1000 €)	100	120	150	100
Total annual cost (1000 €)	1382	1227	1240	984
LNG production cost (€ l^{-1})	0.384	0.341	0.344	0.273
Mark up 10% (€ l^{-1})	0.422	0.375	0.379	0.301

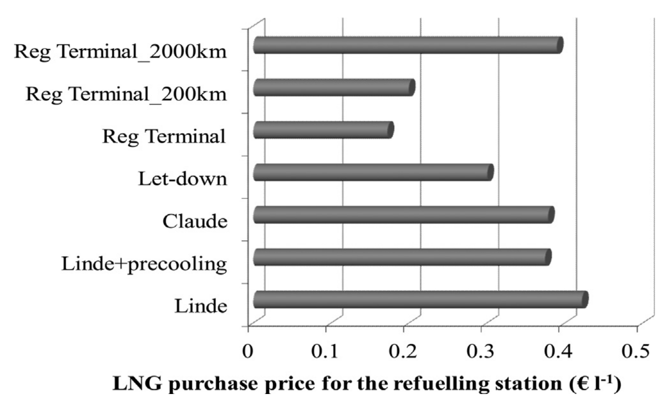

Fig. 8. LNG purchase price at the refuelling station considering different supply options.

Table 4
Results of the comparative analysis on the performance of the different liquefaction cycles.

Cycle	P_{max}	P_{min}	$T_{pre\text{-}cooling}$	$\dot{W}_{comp}$	$\dot{W}_{chiller}$	$\dot{W}_{exp}$	$\dot{W}_{net}$	Specific work requirement	
	MPa	MPa	°C	kW	kW	kW	kW	kWh kg^{-1} $_{LNG}$	%
Linde	20.00	0.10	–	370	–	–	370	2.10	66
Linde+pre-cooling	20.00	0.10	-25°C	189	18	–	207	1.18	78
Claude	5.00	0.10	–	214	–	37	177	1.01	80
Claude+pre-cooling	5.00	0.10	-25 °C	181	17	27	171	0.98	81
Let-down plant	7.50	2.50	–	–	–	35	-35	-	100

Fig. 9. High pressure pipeline in Italy (Snam, 2009).

and it is sent back to cool the main stream. The natural gas to be liquefied is an external stream. This process is more complex and requires several heat exchangers and expansion devices, but it achieves higher efficiencies than methane expansion cycles (see Table 4). For example the mixed refrigerant cycle developed by SINTEF for small scale liquefaction plants claims an efficiency in the range of 0.6–0.9 kW h kg_{LNG}^{-1} (Neksa and Brendeng, 2007), while another MRC presented by Gong et al. (2007) states an efficiency of 0.9–1.0 kW h kg_{LNG}^{-1}.

Instead the liquefaction by liquid nitrogen vaporisation can be used when liquid nitrogen is available in terms of quantity and affordable prices (for example near air separation plants) and a small amount of methane has to be liquefied, because this process is extremely simple, but with a very low thermodynamic efficiency for the whole system, aspect that can be overcome by the economic feasibility of the project. A process using liquid nitrogen together with liquid carbon dioxide is suggested as an option for offshore plants (Aspelund, 2006).

Comparing the energetic performance of the abovementioned liquefaction cycles with those of base-load plants, where typically cascade or mixed refrigerant cycles are used, that have efficiencies of 0.375 kW h kg^{-1} (Remeljej and Hoadley, 2006), it is possible to note that the simplicity of the cycle affects considerably the efficiency that can be achieved, but this is acceptable for micro-scale applications where investment costs take a great role.

4.2. Economic evaluation of the liquefaction technologies

The economic evaluation is aimed at assessing the LNG production cost and it has been performed considering the capital cost of the plants and the operating costs composed of energy cost, labour, maintenance and all the other expenses that can be considered fixed costs. The hypothesis assumed in the analysis are:

- capital costs have been assessed on the basis of authors' knowledge (Arteconi et al., 2011);
- Amortisation period: 10 years;
- maintenance cost: 2.5% of capital investment;
- labour cost: 20 € h^{-1} per person for 360 working days;
- energy price: natural gas 0.35 € Sm^{-3} and electricity 0.14 € kW h^{-1} (prices on the Italian market) (MSE, 2012).

In Table 5 the results of the economic analysis are reported. The Claude cycle with pre-cooling has not been included because considered not attractive due to the low energy efficiency improvement it produces while asking for a capital cost increase.

The let-down plant gives the lower production cost, followed by the Linde cycle with pre-cooling and the Claude cycle.

Fig. 8, instead, shows a comparison between the LNG production cost when it is liquefied from pipeline gas by means of a micro-scale liquefaction plant and when it is bought at a regasification terminal. In the latter case, the LNG purchase price for the refuelling station depends on the distance from the terminal to the refuelling station itself and it ranges between 0.20–0.39 € l^{-1} with varying the transportation distance between 200 and 2000 km from previous evaluations. This confirms that when the liquefaction efficiency is about 80% (Linde cycle with pre-cooling or Claude cycle), the price of LNG from a micro-scale plant can be compared with the price of LNG from a regasification terminal, at least for terminals at great distance from the refuelling station site. Amongst the considered cycles, the let-down plant is the most competitive with the LNG purchased at the terminal. This solution is particularly interesting in Italy where the pipeline network is widespread and the high pressure pipelines cross the Country from the North to the South, allowing to reach easily every place, as shown in Fig. 9.

5. Conclusions and remarks

The purpose of this paper was to analyse the potential of LNG as vehicle fuel with particular reference to the Italian scenario. Generally speaking LNG is an environmental friendly fuel, attractive for heavy duty vehicles, because of reduced on-board weight and space requirements, thanks to its high energy density. Due to the limited environmental impact LNG is receiving attentions as alternative fuel and there are programs to overcome the barriers to its diffusion, as for example the clean fuel strategy by the European Union.

It is authors' opinion that Italy is a fertile Country for this new fuel. In fact the previous successful experience with CNG could be helpful for the uptake of the new fuel LNG. The market is mature, industrial stakeholders exist and the Government has a favourable policy towards NG fuels. Also the environmental concerns and the European environmental policy will represent a boost for LNG introduction, as well as the pollution restrictions in the maritime sector in the Mediterranean sea, that will help the establishment of a proper LNG supply chain. Indeed in Italy the main weak point for LNG as fuel is its distribution and particularly the supply process. Thus, in order to help the uptake of this alternative fuel it is important to address mainly, together with the problem of lack of regulations and standards in the field, the distribution strategy.

The option of purchasing LNG at regasification terminals to supply the refuelling stations is made difficult by the unavailability of Italian terminals where spot cargos are sold. However the analysis performed has shown that this option is economically attractive up to terminal distances of 2000 km, also thanks to low LNG terminal purchasing price. The liquefaction on site is more interesting for those places farther from LNG terminals (the Southernmost regions considering the Barcelona terminal). In Italy the NG grid is well spread, so that liquefaction allows to supply almost every site. For the economic feasibility of this option, a low NG pipeline price has a central role and a direct involvement of natural gas Utilities in the business model of such supply option is of paramount importance.

In case of liquefaction on site, at the scale of the considered application, liquefaction technologies with limited capital costs are advisable. For this reason methane expansion cycles have been analysed in this study with the aim at assessing the LNG production cost by means of liquefaction. Amongst them Linde cycle with a pre-cooling stage and Claude cycle have shown a good energy efficiency. Moreover it has been put in evidence that let-down plants, built to exploit the pressure reduction in the conjunction points between the higher pressure and the lower pressure pipelines, are the best option to produce LNG on site. In fact the LNG production cost is comparable with the current LNG purchase cost at the regasification terminal and the more the regasification terminal is distant from the refuelling station the more the liquefaction on site becomes a feasible option.

Concluding, this paper is meant to highlight the criticality of LNG supply for the uptake of the new alternative fuel and to give indications on the best supply options and parameters that affect them in order to procure a useful evaluation instrument to support the LNG introduction in the Italian market.

References

Andreola, M., 2012. Rolls Royce: The Integrator for Environ-Shipping, ENA Ecodesign Conference. Ancona.

Arteconi, A., Brandoni, C., Bartolini, C.M., Polonara, F., 2010a. Greenhouse Gas Emissions of Heavy-Duty Vehicles Fuelled by Natural Gas. IANGV 2010. Roma.

Arteconi, A., Brandoni, C., Evangelista, D., Polonara, F., 2010b. Life cycle Greenhouse Gas analysis of LNG as a heavy vehicle fuel in Europe. Applied Energy 87, 2005–2013.

Arteconi, A., Brandoni, C., Santori, G., Polonara, F., 2011. Micro-scale LNG liquefaction plants. In: Proceedings of the 23rd International Congress of Refrigeration, Paper 489, 21–26 August 2011, Prague.

Arteconi, A., Pacetti, M., Polonara, F., 2012. A techno-economic optimization for micro-scale LNG plants. In: Proceedings of the 12th International Conference on Cryogenics IIR/IIF, Paper 040, September 11–14, 2012, Dresden, Germany.

Arteconi, A., Polonara, F., 2012. LNG as vehicle fuel in Italy. In: Proceedings of the 12th International Conference on Cryogenics IIR/IIF, Paper 041, September 11-14, 2012, Dresden, Germany.

Aspelund, A., 2006. A novel concept for offshore production of LNG. In: Proceedings of the International Conference on Cryogenics IIF/IIR, Prague.

Chen, Q.-S., Wegrzyn, J., Prasad, V., 2004. Analysis of temperature and pressure changes in liquefied natural gas (LNG) cryogenic tanks. Cryogenics 44, 701–709.

Chrz, V., Emmer, C., 2003. Medium size LNG technology on progress. In: Proceedings of the International Congress of Refrigeration, Paper 309, Washington, D.C.

Engerer, H., Horn, M., 2009. Natural gas vehicles: an option for Europe. Energy Policy 38, 1017–1029.

European Commission (EC), 2001a. Green Paper: Towards a European Strategy for the Security of Energy Supply, Luxembourg. 105p.

European Commission (EC), 2001b. White Paper: European Transport Policy for 2010: Time to Decide. Luxembourg. 119p.

European Environment Agency (EEA), 2011. Greenhouse Gas Emission Trends and Projections in Europe, Report no. 4/2011.

European Union (EU), 2013. EU Launches Clean Fuel Strategy, Brussels 24 January 2013. 〈http://europa.eu/rapid/press-release_IP-13-40_en.htm〉 (last accessed 31.07.13).

Federal Energy Regulatory Commission (FERC), 2012. World LNG Estimated December 2012 Landed Prices. 〈www.ferc.gov/market-oversight/othr-mkts/lng.asp〉 (last accessed 03.12.12).

GHW, GasHighWay, 2009. 〈www.gashighway.net〉 (last accessed 31.07.13).

Gong, M., Wu, J., Zhang, Y., Zhou, Y., 2007. Exergy analysis of a small-scale LNG process utilizing a commercialized refrigeration compressor. In: Proceedings of the 22nd International Congress of Refrigeration IIF/IIR, Beijing.

Hekkert, M.P., Hendriks, F.H.J.F., Faaij, A.P.C., Neelis, M.L., 2005. Natural gas as an alternative to crude oil in automotive fuel chains well-to-wheel analysis and transition strategy development. Energy Policy 33, 579–794.

International Maritime Organization (IMO), 2011, Pollution prevention. 〈http://www.imo.org/ourwork/environment/pollutionprevention/airpollution/pages/sulphur-oxides-%28sox%29-%E2%80%93-regulation-14.aspx〉 (last accessed 31.07.13).

Janssen, A., Lienin, S.F., Gassmann, F., Wokaun, A., 2006. Model aided policy development for the market penetration of natural gas vehicles in Switzerland. Transportation Research: Part A 40, 316–333.

Lage, M., 2012. Is LNG the Best Solution for Long-Distance Transport? The Small-Mid Scale LNG Summit 2012. Amsterdam, The Netherlands.

MSE, Ministry of Economic Development, 2012. 〈http://dgerm.sviluppoeconomico.gov.it/dgerm/bphitalia.asp?txtAnno=2013&txtMese=7&txtGiorno=29〉 (last accessed 03.12.12).

Neksa, P., Brendeng, E., 2007. Small scale natural gas liquefaction plants. In: Proceedings of the 22nd International Congress of Refrigeration IIF/IIR, Beijing.

NGVA Europe, 2011. NGVs and Refuelling Stations in Europe. 〈http://www.ngvaeurope.eu/european-ngv-statistics〉 (last accessed 03.12.12).

Querol, E., Gonzalez-Regueral, B., García-Torrent, J., García-Martínez, M.J., 2010. Boil off gas (BOG) management in Spanish liquid natural gas (LNG) terminals. Applied Energy 87, 3384–3392.

Remeljej, C.W., Hoadley, A.F.A., 2006. An exergy analysis of small-scale liquefied natural gas (LNG) liquefaction processes. Energy 31, 2005–2019.

Sayyaadi, H., Babaelahi, M., 2010. Thermoeconomic optimization of a cryogenic refrigeration cycle for re-liquefaction of the LNG boil-off gas. International Journal of Refrigeration 33, 1197–1207.

Snam, 2009. Rete nazionale dei gasdotti (In Italian). ⟨www.snamretegas.it⟩ (last accessed 31.07.13).
Sterner, T., 2007. Fuel taxes: an important instrument for climate policy. Energy Policy 35, 3194–3202.
Stryjek, R., Vera, J.H., 1986. PRSV: an improved Peng–Robinson equation of state of pure compounds and mixtures. Canadian Journal of Chemical Engineering 64, 323–333.
Suurs, R.A.A., Hekkert, M.P., Kieboom, S., Smits, R.E.H.M., 2010. Understanding the formative stage of technological innovation system development: the case of natural gas as an automotive fuel. Energy Policy 38, 419–431.
UNECE, 2003. United Nations Economic Commission for Europe, Working Party on Gas and Inland Transport Committee, Blue Corridor Project—Final Report.
UP Unione Petrolifera, 2012. Statistiche economiche, energetiche e petrolifere. November 2012. (In Italian).
Walker, G., 1983. Cryocoolers—Part1: Fundamentals. Plenum Press, New York and London p. 365.
Yeh, S., 2007. An empirical analysis on the adoption of alternative fuel vehicles: The case of natural gas vehicles. Energy Policy 35, 5865–5875.