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THE USE OF THE NATURAL-GAS PIPELINE INFRASTRUCTURE FOR HYDROGEN TRANSPORT IN A CHANGING MARKET STRUCTURE

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Abstract

In this paper, the transport and distribution aspects of hydrogen during the transition period towards a possible full-blown hydrogen economy are carefully looked at. Firstly, the energetic and material aspects of hydrogen transport through the existing natural-gas (NG) pipeline infrastructure is discussed. Hereby, only the use of centrifugal compressors and the short-term security of supply seem to constitute a problem for the NG to hydrogen transition. Subsequently, the possibility of percentwise mixing of hydrogen into the natural-gas bulk is dealt with. Mixtures containing up to 17 vol% of hydrogen should not cause difficulties. As soon as more hydrogen is injected, replacement of end-use applications and some pipelines will be necessary. Finally, the transition towards full-blown hydrogen transport in (previously carrying) natural-gas pipelines is treated. Some policy guidelines are offered, both in a regulated and a liberalised energy (gas) market. As a conclusion, it can be stated that the use of hydrogen-natural gas mixtures seems well suited for the transition from natural gas to hydrogen on a distribution (low pressure) level. However, getting the hydrogen gas to the distribution grid, by means of the transport grid, remains a major issue. In the end, the structure of the market, regulated or liberalised, turns out not to be important.

Keywords: hydrogen, natural gas, mixtures, transition, pipeline infrastructure, liberalised market.

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Nomenclature

C = proportionality constant = 0.000129 [-]

d = relative density compared to air [-]

D = inner diameter [mm]

e = pipeline efficiency [-]

f = friction factor [-]

H_s = higher heating value [MJ/Nm^3]

K_m = compressibility factor, corresponding to p_m [-]

$K_{m'}$ = compressibility factor, corresponding to $p_{m'}$ [-]

L = length [km]

p_1 = inlet pressure [kPa]

p_2 = outlet pressure [kPa]

p_m = upper mean pressure [bar]

$p_{m'}$ = lower mean pressure [bar]

p_n = 1.013 [bar]

Q = flow rate [Nm^3/h]

T = gas temperature [K]

T_n = 273.16 [K]

V_{geom} = volume of pipeline [m^3]

$V_{storage,n}$ = volume of stored gas [Nm^3]

W_s = Wobbe-index, based on the higher heating value [MJ/Nm^3]

Z = compressibility [-]

1. Introduction

Although there are still numerous questions about the concrete realisation of a possible transition towards a hydrogen economy, hydrogen could play an important role in our future energy supply. Production methods, end-use technologies and storage applications are well known (e.g. Ogden [1], Padro and Putsche[2]), although there is a need for further research before a real commercial breakthrough can be expected. As far as the transport and distribution of hydrogen towards the end user is concerned, also further research is still needed, and some practical questions should be addressed. Can the existing natural-gas pipeline infrastructure be used? Are there any energetic or material restrictions? To what extent is it possible to mix hydrogen with natural gas? Does a liberalised gas market constitute a problem for mixing of hydrogen and natural gas?

This paper first makes a well-balanced technical analysis of the energetic and material aspects of hydrogen transport through pipelines (in Sections 2 and 3, respectively), up to the possibility of percentwise mixing hydrogen into a natural-gas bulk (Section 4). However, concerning the transition towards the full-blown hydrogen transport in (previously carrying) natural-gas pipelines, an important question to be resolved is whether the technical aspects are perhaps overshadowed by the liberalised character of the gas market (Section 5).[1]

[1] The authors assume the existence of hydrogen as an energy carrier (and a certain demand for it) and wish to study how it can be transported, thereby disregarding for the energy sources that have been used to produce the hydrogen. Although one could argue that only clean-coal or gas technologies (with carbon capture and storage) and excess renewable electric energy should qualify for the production of hydrogen, we do not wish to exclude hydrogen production by nuclear power or through large-scale electrolysis from superfluous electricity. We leave it to market forces and policy guidance to determine the production mix for hydrogen. It then seems reasonable to investigate whether, to a certain extent, the existing, well-developed natural-gas pipeline infrastructure could be used to transport and distribute this hydrogen. The use of hydrogen-natural gas mixtures is further justified in Section 5.1.

2. Energetic aspects of hydrogen transport through pipelines

The existing natural-gas transport network mainly consists of pipelines, compression stations and pressure-reduction stations. On the one hand, this network serves to transport a sufficient amount of energy towards any end user (actually a power flow). On the other hand, the network is also used to store natural gas whenever the gas supply exceeds the demand. This (short-term) storage of natural gas in pipelines is called linepack, which allows an almost continuous supply of natural gas into the network, despite a strongly fluctuating demand pattern (viewed differently, the linepack allows the demand side to change its offtake at will, independently of the injection into the pipeline). More storage, of course, implies higher pressures.

To meet the energy demand, the flow rate of natural gas has to be sufficiently high. This flow rate, in turn, is controlled by the pressure drop in the pipeline. The energy flow through a pipeline is described by (KVBG [3], Cerbe [4])

$$Q = C.D^{2.5}.e.\sqrt{\frac{\left(p_1^2 - p_2^2\right)}{d.Z.T.L.f}} \quad , \qquad (1)$$

whereby Q = normal flow rate [Nm^3/h]

C = proportionality constant = 0.000129 [-]

D = inner diameter [mm]

e = pipeline efficiency [-]

p_1 = inlet pressure [kPa]

p_2 = outlet pressure [kPa]

d = relative density compared to air [-]

Z = compressibility [-]

T = gas temperature [K]

L = length [km]

f = friction factor [-]

[Nm^3/h] = normal cubic metre/hour

The Higher Heating Value (HHV) of hydrogen amounts to 13 MJ/Nm^3, whereas the HHV of natural gas equals approximately 40 MJ/Nm^3. Therefore, to satisfy the same energy demand, the volume of hydrogen to be transported has to be three times that of natural gas. Luckily, the density of hydrogen is nine times smaller than that of natural gas. From equation (1), it then can be seen that a flow rate of hydrogen, three times larger than that of natural gas, results in approximately the same pressure drop, being the critical parameter in a pipeline network [3] [4].

However, also other parameters such as Z and f can vary with pressure or flow rate. Detailed calculations show that, assuming an unchanged pipeline and pressure drop, hydrogen is able to transport 98% of the energy compared to lean natural gas and 80% compared to rich natural gas[2]. An overview of these calculations is given in figure 1 (whereby the full range from 0 to 100 vol% of hydrogen, mixed with natural gas, is looked at). The percentages just quoted can be seen for 100% hydrogen, on the right-hand side of Figure 1.

The possible linepack in a pipeline is strongly influenced by the flow rate. The lower the flow rate, the more storage becomes possible [4]. An analytical formula to determine the linepack in a pipeline is given by

$$V_{storage,n} = V_{geom} \cdot \left(\frac{p_m}{K_m} - \frac{p_{m'}}{K_{m'}} \right) . \frac{1}{p_n} . \frac{T_n}{T} \, , \tag{2}$$

[2] Lean natural gas is low-calorific natural gas (L-gas) with a HHV of approximately 37.7 MJ/Nm^3 and a Wobbe number between 41 and 47 MJ/Nm^3 (e.g. Slochteren gas). Rich natural gas is high-calorific natural gas (H-gas) with a HHV of 40 MJ/Nm^3 or more and a Wobbe number between 48 and 58 MJ/Nm^3.

whereby p_m can be calculated as follows:

$$p_m = \frac{2}{3}.\frac{p_1^3 - p_2^3}{p_1^2 - p_2^2} = \frac{2}{3}.\left(p_1 + p_2 - \frac{p_1.p_2}{p_1 + p_2} \right). \qquad (3)$$

and, $V_{storage,n}$ = volume of stored gas, referenced back to 'normal' conditions at p_n and T_n [Nm^3/h]

V_{geom} = volume of pipeline [m^3]

T_n = 273.16 [K]

p_m = upper mean pressure [bar]

T = gas temperature [K]

$p_{m'}$ = lower mean pressure [bar]

T = gas temperature [K]

K_m = compressibility factor [-]

p_1 = inlet pressure [kPa]

$K_{m'}$ = compressibility factor [-]

p_2 = outlet pressure [kPa].

p_n = 1.013 [bar]

In an existing pipeline network, linepack with hydrogen varies between 65% and 71% of linepack with natural gas, depending on the normal flow rate. However, these percentages are only valid when linepack is expressed as a volume. What really is important, is the linepack-energy, since satisfying the energy demand always prevails. So, taking into account the energy content of hydrogen and natural gas, the linepack-energy of hydrogen can be more than four times smaller than this of natural gas, which may undermine the short-term security of supply during one day. This is illustrated in figure 2 (compare values at 0% H_2 with 100% H_2).

3. Material aspects of hydrogen transport through pipelines

Besides energetic considerations, also several material issues require some attention: e.g., the use of the existing compression and pressure-reduction stations, hydrogen embrittlement and leakages.

Two types of compressors can be distinguished: centrifugal and piston compressors. As far as piston compressors are concerned, the working gas that is used, is of no importance. However, using hydrogen in centrifugal compressors, requires compression of a volume three times as large as when natural gas is used. Furthermore, to obtain the same pressure ratio, the rotational velocity to compress hydrogen must be 1.74 times higher than to compress natural gas. Unfortunately, this rotational velocity is limited by the material strength, which can cause problems when hydrogen is sent through the existing pipeline infrastructure (Vanderoost et al, [5]).

Due to the Joule-Thompson effect, reducing the pressure of natural gas causes its temperature to decrease with 0.5 ^{o}C/bar, whereas the temperature rises with 0.035 ^{o}C/bar when the pressure of hydrogen is reduced. So, throttling hydrogen from 80 bar to 15 bar, results in a temperature rise of 2 ^{0}C, which does not cause any problem (Vanderoost et al, [5]).

The risk of hydrogen embrittlement is complicated to predict. It does not only depend on the material of the pipeline, but also on the pipeline's history. The larger the pressure fluctuations in the past have been, the higher the risk of hydrogen embrittlement and material fatigue. Therefore, only intensive testing of pipelines and welds will give a definitive answer about this potential problem (Prager [6], Korb [7]).

The volumetric losses of hydrogen by leakage are always larger than those of natural gas, but the energetic losses are always smaller. Furthermore, the quantitative amount of losses strongly depends on the material of the pipeline. The leakage risk is considerably large in cast iron and fibrous cement pipelines. However, on the distribution level, currently mostly polyethylene (PE) pipelines are used. Diffusion of hydrogen through PE pipelines is five times higher than diffusion of natural gas, but still negligible. Calculations have shown that the yearly loss of hydrogen by leakage amounts to approximately 0.0005% - 0.001% of the totally transported volume (Scholten and Wolters [8], Florisson [9], Polman et al. [10]).

4. Percentwise mixing of hydrogen into a natural-gas bulk

Several studies have shown that injection of up to 17 vol% of hydrogen into the natural-gas network, should not cause difficulties (Polman et al. [10], Janssen van Rosmalen et al. [11], Kop [12]). Mixing of higher percentages of hydrogen into the natural-gas bulk, however, does require attention, although we now show that the problems do not seem to be insurmountable. The effect on the Wobbe-index, the linepack and the pressure drop is significant, as shown in the figures 3, 2 and 1, respectively. The Wobbe-index determines to which family gases belong and is a measure for exchangeability of gases in gas burners, and consequently determines whether they can be used in domestic applications[3]. It is calculated as follows:

$$W_s = \frac{H_s}{\sqrt{d}} \tag{4}$$

[3] The authors do not necessarily promote the use of hydrogen for combustion in boilers for space heating. However, when hydrogen becomes available by means of pipeline distribution (with mixtures ranging from 0% to 100%), it should not be excluded that end users with gas-fired heating equipment want to continue using their furnaces, albeit perhaps for a transitional phase.

whereby W_s = Wobbe-index, based on the higher heating value [MJ/Nm^3]
H_s = higher heating value (HHV) [MJ/Nm^3]

d = relative density compared to air [-]

The boundaries within which the Wobbe number must lie for common rich natural-gas burners are 48 and 58 MJ/Nm^3. When lean natural gas is used in standard burners, the Wobbe number has to lie between 41 and 47 MJ/Nm^3. From figure 3, it then can be seen that for lean natural-gas burners, up to 98 vol% of hydrogen can be added. For rich natural gas, up to 45 vol% of hydrogen can be injected. Also mixtures containing more than 98 vol% of hydrogen are useable. Having said that, currently some countries (e.g. France and Belgium) have chosen to invest in flexible burners, which can tolerate gases with a Wobbe number within the whole range of 41 to 58 MJ/Nm^3, i.e., they can tolerate both lean and rich natural gas. Nevertheless, those currently installed flexible burners would not be able to cope with the full range of hydrogen mixed into NG due to problems with sealing, flame detection.

The most important effect of using hydrogen in burners, boilers or gas engines, is the increase of the flame speed, which brings along the risk for flashback. This problem could be by-passed by means of a leaner combustion process. In general, the flame detection system, the burner head and the sealings will need adjustment when hydrogen or hydrogen-natural gas mixtures are used. A possible solution to avoid multiple adjustments each time the composition of the input fuel is changed, is the use of multifunctional devices which can run both on natural gas and pure hydrogen, as on any mixture of these two. Presently, these applications are being developed and the first test results (efficiency, emissions, safety) seem satisfactory (Hoelzner and Szyszka [13], Schucan [14], Solar Hydrogen [15], Ilbas et al. [16], Akansu et al. [17]).

Figure 3 clearly shows that mixtures containing around 75 vol% of hydrogen perform the worst with regard to the Wobbe number. A similar behaviour is found when the pressure drop is considered (figure 1), although, for the range of 65% - 85% depending on the sort of NG. However, most negative effects start disappearing when the amount of hydrogen added, exceeds 90 vol%.

Since no problems are expected if less than 17 vol% of hydrogen is injected, it seems logical that this would be the first step towards a hydrogen economy. However, from an economic point of view, the liberalised gas market may throw a spanner. Since some energy companies will still sell natural gas, while others offer hydrogen or hydrogen-natural gas mixtures, or a combination of these, it is hardly imaginable that all these 'products' will be transported through the same pipeline network, which provides all customers' demand.

5. Transition towards full-blown hydrogen transport in natural-gas pipelines

5.1. General issues

In what follows, the reader should clearly distinguish between the distribution (i.e., low pressure) grid and the transport (i.e., high pressure) grid.

It goes without saying that hydrogen as an energy carrier will only be a realistic option if and when it becomes economically favourable. Here, "economic" has to be interpreted in a broad sense, meaning that the external costs for all energy options also have to be included in the overall comparison. When these conditions are met, the question can be raised how the transition from natural gas to hydrogen will take place. The considerations at the end of section 4 make clear that, although it could be a first step towards the widespread use of hydrogen, the use of hydrogen-natural gas mixtures containing over 17 vol% of hydrogen, is not self-evident, unless certain standards are enforced by governments by means of taxes or subsidies. Therefore, it should be investigated whether the immediate use of pure hydrogen, instead of a transition period with mixtures, might perhaps prove to be a more realistic scenario.

Technically seen, this drastic changeover should be possible. After all, historically most European countries have switched from city gas (a mixture of about 50% CO and 50% H_2) to natural gas literally overnight. Hereby, the grid was divided into different sectors and during one night, the replacement of city gas by natural gas was carried out in one particular sector. In the subsequent week, all end-use applications were modified or replaced and natural gas became the new energy carrier. It seems very unlikely that this scenario can be repeated for the transition from natural gas to hydrogen. The reasons are threefold: firstly, the distribution network is almost three times larger than it was 40 years ago. This would make such a changeover very time-consuming. Secondly, the absence of a high-pressure transport grid in the 1960's made such transition far less complicated than it would be now. Thirdly, as the number of end-users has drastically been increased by now, the necessary replacement of all end-use applications will be very cost-intensive.

Another option, the installation of a parallel pipeline network for hydrogen, could theoretically also be considered as a plausible solution for the introduction of hydrogen into our society. This approach might be perfectly feasible for the high-pressure transport network, but most likely it will bring serious problems about for the distribution network due to a lack of space. Thus, since an immediate and entire switch from natural gas to hydrogen does not seem to be a realistic scenario, both for the distribution and the transport grid (and this is independent of the energy-market structure, since we have not even mentioned that aspect in this section 5.1), a transition period with mixtures, certainly has to be considered as a serious option.

For technical reasons, any injection of hydrogen into the natural-gas bulk initially should take place at the medium or low-pressure grid, immediately after the pressure-reduction stations. On the one hand, backflow from the medium or low-pressure grid to the high-pressure transport grid is effectively impossible, which allows to carry out the transition process on both levels strictly separated. On the other hand, no compressors are used in the medium or low-pressure distribution grid, which facilitates the use of the pipeline infrastructure for hydrogen transport.

5.2. Transition towards hydrogen in a regulated energy market

In general, a regulated energy market is entirely controlled by the government or a monopolist. In this case, an injection of hydrogen into the natural-gas bulk will only take place when the regulatory authorities impose it, possibly invoking environmental or social-economic – thus also considering external costs – reasons. A logical first step then would be the injection of up to 17 vol% of hydrogen into the medium and low-pressure grid. As far as Flanders (the Northern part of Belgium) is concerned, this would come down to approximately 62 injection points in order to provide every small customer with the same hydrogen-natural gas mixture. Due to the expected transition from lean to rich natural gas in the not too far future, every newly-installed end-use application in Flanders must currently be capable of burning gases that have a Wobbe number between 41 and 58 MJ/Nm^3. Therefore, as can be seen from figure 3, a mixture containing no more than 17 vol% of hydrogen only requires some minor adjustments to burners, boilers or gas engines (burner head, flame detection system and sealing). A replacement of these applications will not be necessary in this stadium. As far as small microturbines are concerned, replacement of these units will probably be needed.

In a second phase, more than 17 vol% of hydrogen can be mixed into the natural-gas bulk. This would require any end-use application to be replaced, preferably by a multifunctional device that is capable of handling all kinds of mixtures, up to pure hydrogen. Technically seen, this should not create a problem, since, in order to avoid an overnight replacement of these units, the government could issue new standards for boilers, burners and gas engines some years before this second-phase transition takes place. Of course, when mixtures containing more than 17 vol% of hydrogen are used, not only boilers and burners, but also internal or external-reforming fuel cells may enter the commercial market. Fuel cells, fed by pure hydrogen, will not play any role of importance during this transition scenario, as only mixtures of natural gas and hydrogen will be available at large scale at this moment.

5.3. Transition towards hydrogen in a liberalised energy market

A liberalised energy (gas) market is characterised by different shippers that feed the pipeline infrastructure with their own products. This market structure implies that, at some point, natural gas and hydrogen will become competitive energy carriers in the energy market. Only economic considerations will then incentivise shippers to offer hydrogen to the customers, while others will still be offering natural gas. From this point of view, it is difficult to see how a transition from pure natural gas to pure hydrogen can take place through one single (high and low-pressure) pipeline network controlled by one grid operator, but fed by different shippers.

However, even in a liberalised market the government can require that the gas that is supplied to the customers, connected at the distribution grid, meets certain standards. In a first phase, the presence of up to 17 vol% of hydrogen in the natural-gas bulk, could be one of these standards. Also taxes could be used to encourage shippers to mix a certain amount of hydrogen into the natural-gas pipeline infrastructure. The resulting, necessary adjustment of end-use applications of course will have to be coordinated by the government as well in this case.

In a second phase, here again, the government can issue new standards in order to replace every end-use application by a multifunctional device, including fuel cells with reforming. This decision is unrelated to the products that are supplied by the shippers, but it offers the market the opportunity to evolve more and more to a hydrogen-based economy if this would be economically favourable. On the whole, it can be concluded that, on the distribution level, a transition to hydrogen does not seem to meet any additional problems due to the liberalised character of the gas market.

5.4. The supply of hydrogen in a transitory economy

Even though the transition from natural gas to hydrogen seems to be achievable by gradually mixing in hydrogen into the natural-gas bulk, the question remains how a sufficient amount of hydrogen can be supplied to the distribution grid. In a regulated energy market, the building of a hydrogen transport grid, parallel to the high-pressure natural-gas grid, might be an option, if it were not for the cost. It will probably turn out to be a solution that is far too expensive, although technically perfectly feasible.

Another option might be to install hydrogen-production units near the injection points. This can also offer a solution for the 'short-term security of supply' problem because of a smaller linepack for H_2 (see section 2), by producing a surplus of hydrogen and storing it in large vessels or tanks. This approach should, theoretically seen, be possible in both a regulated and a liberalised gas market. However, in a liberalised market, who will take care of the hydrogen supply and/or production? The government may well be able to impose certain standards on the composition of the gas at the distribution grid, but if no one takes the initiative or is willing to invest in these hydrogen-production units, nothing will change. Of course, much will depend on the market conditions at that very moment.

A third possibility, which actually lies beyond the scope of this paper, but certainly is worth mentioning, is the interaction between the energy and the transportation sector[4]. It is very unlikely that a transition to hydrogen only will take place in the energy sector. The transportation sector could also evolve towards hydrogen as an energy carrier, which implies that hydrogen-filling stations may arise throughout the country. Some of these stations would make use of their own hydrogen-production units, which then could be applied to deliver hydrogen to the injection points. However, for now it remains a question mark whether the capacity of these units will be sufficient to do so.

[4] We distinguish between "transportation", by which we mean "vehicles and mobility", and "transport", by which we mean moving around gases in pipelines over long distances at high pressure (the latter to be distinguished from distribution of gas over short distances and at low pressure).

5.5. Transition to hydrogen on the transport level

Gradually mixing in hydrogen into the distribution grid might be a first step to bring about the transition towards a hydrogen economy. However, in the long run, the high-pressure transport grid can no longer be neglected. We will mention some issues here that have to be kept in mind, however, without trying to solve the entire issue.

Firstly, in contrast with the distribution grid, compressors are a part of the transport grid. Since the use of hydrogen in centrifugal compressors might cause the used materials to fail because of the required higher pressure ratio, it is strongly recommended to use piston compressors as soon as hydrogen is fed into the transport grid. Secondly, as most European countries are transit countries for the transport of gas, the decision to start using hydrogen can only take place on a European level, not on a national one. And thirdly, during a transition period with almost no fuel cells present yet, hydrogen will likely be used for space heating (as part of the NG mixture), not to generate electricity. This means that the large, centralised CCGT units will still be needed to generate a sufficient amount of electricity. It is, however, not clear whether these units can cope with hydrogen as an input gas (or mixtures with a large fraction of hydrogen in natural gas). Also the large industrial users, which are directly connected to the transport grid, might experience some problems with the changing characteristics of the gas mixture that is supplied.

6. Conclusions

In the far future, hydrogen might prove to be a competitive and reliable energy carrier. For this reason, worldwide great efforts are made in the field of hydrogen production, storage and end use. Nevertheless, little attention is paid to how these large amounts of hydrogen will be supplied to the customer in a real-life situation. Moreover, it is very unlikely that the step to a hydrogen-based economy will take place from one day to the next. On the contrary, such a fundamental change will certainly be a slow process of several years, or even decades. And this very important, even critical, transition period is too often overlooked when the possibility of a hydrogen economy is considered.

Therefore, this paper has tried to give an overview of the technical and structural aspects that will play an important role during such a transition period. It has not been the intention to provide an answer to all problems that may arise, but it should allow research centres and policy makers to gain a better insight in the entire transition issues. Hereby, the liberalised character of the energy market was kept in mind, as was the possibility to slowly introduce hydrogen into our society by gradually mixing in hydrogen into the natural-gas bulk. Clearly, the technical aspects of the natural-gas pipeline infrastructure and the different end-use applications will play an important role as far as the feasibility of this approach is concerned. In our belief, a transition towards a hydrogen-economy by means of hydrogen-natural gas mixtures, transported and distributed through the existing natural-gas grid, seems to be possible, both in a regulated and in a liberalised energy market. A possible stumbling block for the transition towards massive use of hydrogen, may be the gas-transport grid, regardless of a regulated or a liberalised market.

It is our conclusion that the structure of the market, regulated or liberalised, in itself is not a fundamental problem, but getting the hydrogen gas to the distribution grid, by means of the transport grid is not self evident. Creative solutions are needed in this regard.

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Figure captions

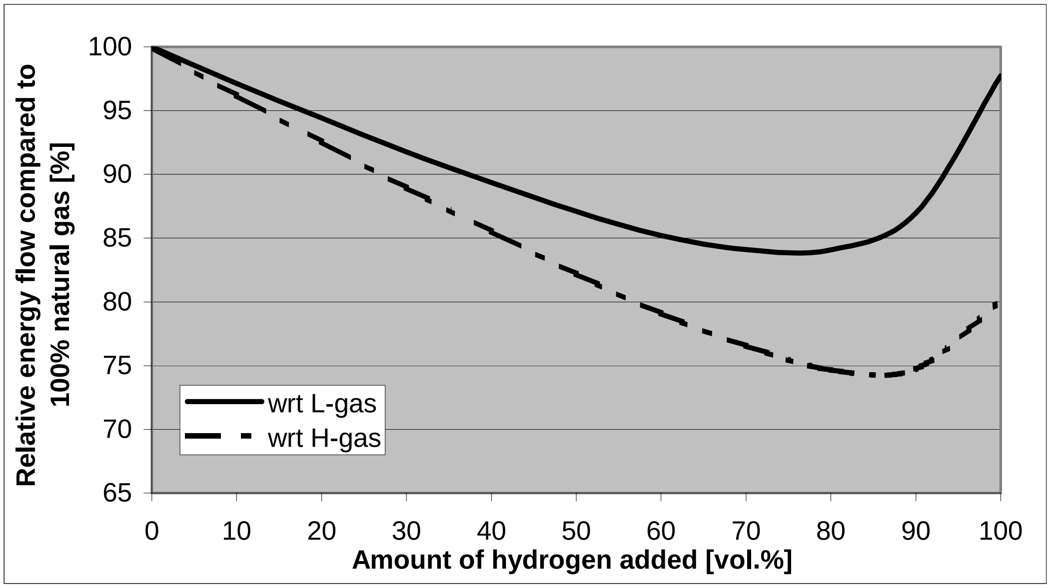

Figure 1: Energy-transport losses for hydrogen and hydrogen-natural gas mixtures, assuming an unchanged pressure drop.

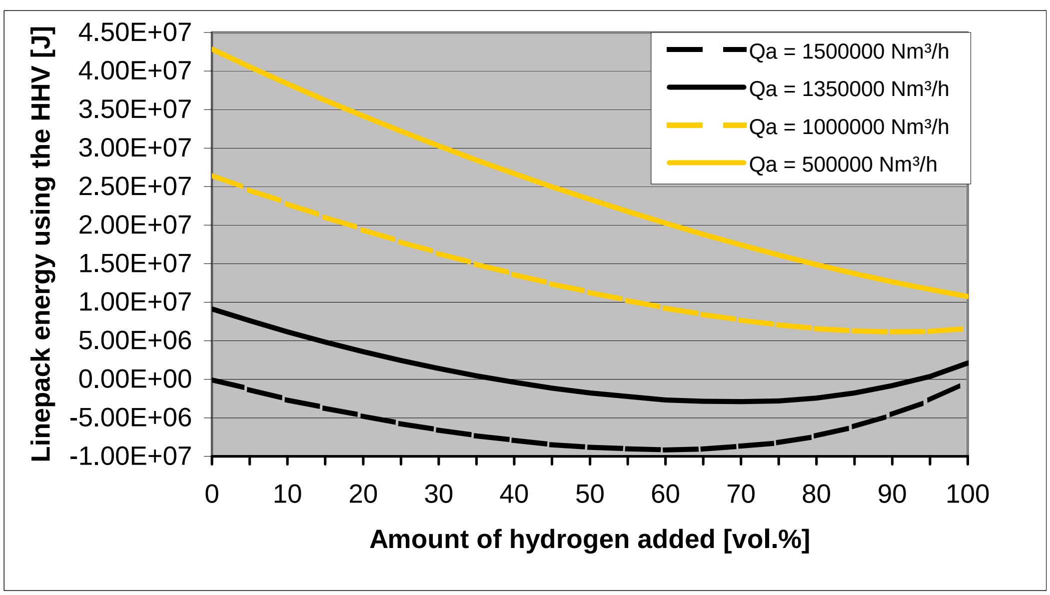

Figure 2: Linepack energy corresponding to different hydrogen-natural gas mixtures (inlet pressure: 67 bar)

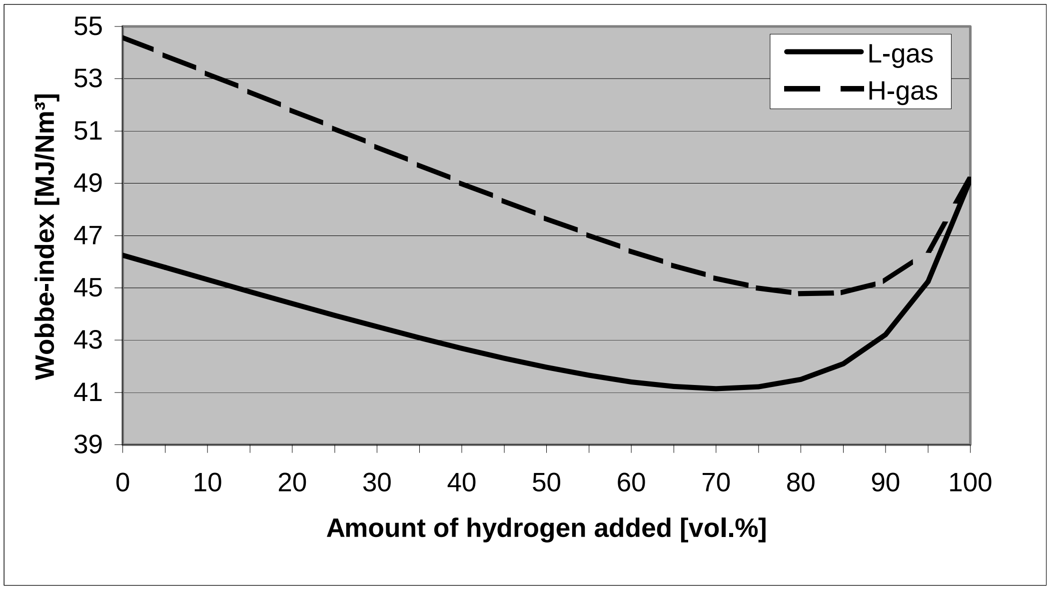

Figure 3: Effect of hydrogen-natural gas mixtures on the Wobbe-index