Requirements for gas quality and gas appliances

Ministerie van Economische Zaken, Rijksdienst voor Ondernemend Nederland (RVO)

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LIST OF ABBREVIATIONS

Dam^3	1000 m^3
DLG	Distribution Limit Gases
ELG	Extreme Limit Gases
GTS	Gasunie Transport Services
LOCAL	JDA LoCal
NGT	Noordgastransport
NH	Noord-Holland
NOGAT	Northern Offshore Gas Transport
QC	Quality Conversion
t.q.	TelQuel
WGT	West Gas Trunk
WI	Wobbe Index
ZH	Zuid-Holland

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EXECUTIVE SUMMARY

Introduction

The gas transmission network in the Netherlands transports two different qualities of gas, low-calorific gas known as G-gas or L-gas and, high calorific gas (H-gas). These two gas qualities are transported in separate networks, and are connected by means of five blending and conversion stations where high-calorific gas can either be blended with low-calorific gas or ballasted with nitrogen to produce gas that can be introduced into the low-calorific, G-gas, network.

The network was originally developed following the discovery of the large Groningen gas field. The Groningen field is low calorific gas. The low-calorific gas from the Groningen field became the standard for the consumers in the Netherlands. Later on, H-gas gas was produced from the so-called small fields in the Netherlands. High-calorific gas is also imported from Norway, Russia and through the LNG terminal in Rotterdam. The H-gas is supplied to industrial end users via approximately 80 connections to the high-calorific network and is also exported to other countries. The standard Wobbe Index bandwidth currently specified for exit points in the gas transmission network for H-gas is 47-55.7 MJ/m^3 (25/0), with a number of regional variations as described in the Ministerial Ruling (MR) for gas quality.

The supply of low-calorific gas from the Groningen field is in decline, and ultimately the future supply to end users will be high-calorific gas. In March 2012, the Minister of Economic affairs declared that all appliances falling under the Gas Appliance Directive (the GAD) should be able to switch to high-calorific gas to prepare for a smooth transition at the end of the lifetime of the Groningen field. For this purpose, a formal notification has been given to the European Commission. However, at the moment it is unclear what the future range of high-calorific gas quality should be; that is, the range of gas quality that appliances falling under the GAD can accept is at present uncertain.

The question posed by the Dutch government is whether or not the government should change the existing notification of the requirements that GAD gas appliances should be able to meet to cope with high-calorific gas, and if so, how and when.

Analysis

The study comprised three major areas of investigation. In the first step, the limitations in appliance performance with varying gas quality were assessed. This assessment is based on a critical analysis of existing data from laboratory experiments on appliances from well-defined field tests and also from a critical analysis of non-experimental information (theoretical studies and evidence-based experience). In the second step, the future ranges of gas quality expected to be supplied in the Netherlands was inventoried, and the possibilities for, and costs of, treating the gases to limit the range of gas quality was assessed. In the third step, the potential of innovation for widening the range of gases acceptable for appliances was assessed. The recommendations summarized below are based on the synthesis of these three elements.

Limitations in appliances

We assessed the existing experimental, theoretical and practical/experiential evidence regarding which bands of Wobbe Index maintain the safety and reliability of the population of H-/E-band appliances installed in the field. In our opinion, the distribution practices in the UK, France, Denmark and Belgium give the best reflection of a practical range for Wobbe Index: the years-long practice in these countries shows that H-/E-band appliance performance with distribution limits in the range 4-5 MJ/m^3 satisfies the national requirements and/or customs for safety and reliability in these countries. We also note that these countries have some form of active maintenance regime. Provided adjustable appliances are properly adjusted, the laboratory experiments assessed support a range of 4-5 MJ/m^3, although these experiments require extra interpretation before being applied to the situation in practice. The theoretical analyses show that the approval regime does not safeguard the intended appliance performance in a number of situations. However, these analyses say nothing about the actual safe and reliable performance of appliances in the field. Therefore, we conclude that a bandwidth of in the range of 4-5 MJ/m^3 can be realized for appliances approved under the GAD.

Future supply

Ultimately, when Dutch indigenous gas production becomes small, gas is expected to be supplied by pipeline imports from Norway and Russia, and as LNG from the worldwide market. The Netherlands is expected to become a net importer from 2025 onwards. The expectation is further that the imported gas will have a Wobbe Index between 51 and 55.7 MJ/m^3 (25/0). The upper limit of 55.7 MJ/m^3 is set by the Dutch government.

This gas quality bandwidth is significantly smaller than the current standard bandwidth permitted in the H-network, from 47 to 55.7 MJ/m^3. The 'small fields' contribute predominantly to the lower half of this range. At the moment an annual volume of 25 bcm is produced from the small fields. By 2032 the total capacity including so-called futures is expected to be almost three times lower than the 2014 capacities. These futures are however uncertain. When the futures are not taken into account, the total capacity will be 15 times lower compared to 2014. In 2032 supply from the small fields will then only be 3% of demand (20% if the futures fully materialize). Excluding futures, the production volume of the small fields decreases to 1 bcm in 2030.

Three cases with different Wobbe Index bandwidths were evaluated: a band of 2 MJ/m^3, significantly narrower than the expected range of import qualities, a wide band of 8 MJ/m3 and a band coincident with the expected future import band of 4.7 MJ/m^3. The results show that the narrow band option requires the most gas treatment, particularly nitrogen ballasting, which given the expected import will be required indefinitely. The costs for gas treatment (especially nitrogen ballasting) will thus recur every year. The widest band allows the widest accommodation of both import gases and residual small-field gases. Referring to the appliance limitations analysis above, not all appliances can handle a band of 8 MJ/m^3 without further gas treatment measures. We note that the potential measures that support the intake of 'off-spec' gas with a Wobbe Index lower than the minimum Wobbe Index of H-gas imports are expected to be temporary. The volume of gas from the small fields is expected to become very small after 2030 as mentioned above. The use of the gas quality management options described here is seen more as a transition measure and not as permanent. In light of the expected gas supply, the widest band gives therefore only a temporary advantage.

For the intermediate band of 4.7 MJ/m^3, the import gases can be easily accepted, but relatively more small-field gases become 'off spec', requiring blending with the H-gas import. The forecast of H-gas imports volumes indicate that sufficient H-gas is available for blending the 'off spec' gas in this case. Ballasting with nitrogen will not be required if the upper Wobbe limit is set at 55.7 MJ/m^3.

Concluding, choosing the intermediate band of 4.7 MJ/m^3 corresponds to the bandwidth of the expected import of future H-gases of 51-55.7 MJ/m^3, and is also within the range of 4-5 MJ/m^3 to which the GAD appliances have been exposed in practice. In this option there are no extra costs for nitrogen ballasting. This range may provide an optimum between appliance performance and expected gas supplies.

Innovation

An inventory has been made to determine the status of the development of innovative products aimed at extending the fuel flexibility of GAD end-use equipment, e.g. by means of active control systems. The inventory is based on interviews with different stakeholders and collecting existing information available, including progress made in existing innovation programs such as SBIR.

It became clear that commercially available (premixed) appliances having active control systems are suited to operate across the entire E-band and for handling abrupt Wobbe fluctuations. We also observed promising developments for (inexpensive) control systems for premixed appliances to extend the fuel flexibility for both new domestic appliances and suitable appliances already installed in the field. Also, a sensor-based hob burner (cooker) is under development to guarantee high performance and capacity while using variable gas quality (L+H band). DNV GL is not aware of any existing developments or innovations to make other type of partially premixed domestic appliances, such as flow-through hot water heaters, suitable for a wide range of gas compositions. To our knowledge, no innovation regarding the development of fuel-adaptive control systems for non-domestic burners is currently being undertaken. However, several control strategies are possible and economically feasible.

Recommendation

Based on the analysis, DNV GL recommends setting the long term quality bandwidth for H-gas at 51 – 55.7 MJ/m^3 (25/0). In this choice, the bandwidth (4.7 MJ/m^3) is within the 4-5 MJ/m^3 with which millions of H-/E-band appliances function in other EU countries, aligning the distribution practice with those in other countries, and complex and costly gas quality management measures are limited. A consistent policy for appliance adjustment using known gas quality is essential for maintaining this band. We recommend updating the existing notification and suggest modifications to the notification as formulated in Appendix A. We further note that in terms of Wobbe Index this band allows room for the accommodation of a reasonable bandwidth for renewable gases.

1 INTRODUCTION

The gas industry in the Netherlands was sparked by the discovery of the large Groningen field. The natural gas from the Groningen field became the standard for the consumers in the Netherlands. Only later high calorific value gas was produced from the so-called small fields in the Netherlands and imported from Norway, Russia and via the LNG terminal. High calorific value gas (so-called H-gas) is supplied to the end users via approximately 80 connections. A separate gas transmission system was developed to accommodate these H-gas flows. These systems are operated separately and are only connected by means of five blending and conversion stations where H-gas can be either be blended with low-calorific gas streams or ballasted with nitrogen in order to produce low-calorific value gas for distribution. These systems have been in stable operation for many years.

The letter of the Minister of Economic Affairs of 12 March 2012 (Long-term policy on gas composition) included a no-regret-measure that appliances falling under the Gas Appliance Directive (the GAD) should be able to switch to high calorific value gas, to prepare for a smooth transition at the end of the lifetime of the Groningen field. Thus, with an eye towards this transition, only appliances that can function on both the future G^+-gas composition and on a future range of H-gases may then be sold. Current GAD appliances that are used for both L-gas and H-gas are designated as E-band appliances, such as $I_{2E.}$

However, there is no agreement in the EU regarding the range of natural gases that can actually be distributed that is guaranteed by the current approval regime, particularly regarding the range of limit gases used in appliance approval, described in EN 437. Since doubt has been cast on whether the full bandwidth of the existing range of H-gases in the Netherlands is guaranteed by the approval regime, the adequacy of the approval regime, specifically in relation to the limit gases, has also been called into question as well as the width of the currently defined range of H-gases in the Netherlands. To provide clarity for the future, the Dutch government has commissioned this study to assess the relation between the choices for the range of gases to be distributed.

The core question the study should answer is the following:

Is it wise for the Dutch government to notify the requirements that gas appliances should be able to meet in order to handle high calorific gas under the Gas Appliances Directive (and the EN 437) differently than it has, and if so, how and when?

Specific questions which need to be answered are:

- Which bandwidth are the current appliances of the appliance category I_{2E} able to handle in practice?
- What possibilities are there to limit the bandwidth of the Wobbe index of the gas to be distributed and what will it cost? What are the pros and cons?
- What possibilities are there to make all new gas appliances suitable for a larger bandwidth by means of innovation and what will it cost? What are the pros and cons?
- What are the experiences of other European countries with the Wobbe bandwidths and how are they dealing with the problem of adjusting gas quality and gas appliances in the long term?

1.1 Approach

In short, the goal of the study is to advise the Dutch government in choosing a range of gas compositions for H-gas that will provide fewest restrictions in supply, while maintaining safety and reliability levels of the end user with the lowest (social) cost.

The approach in the study comprised three major areas of investigation. These areas are depicted schematically as Steps 1-3 in the figure below.

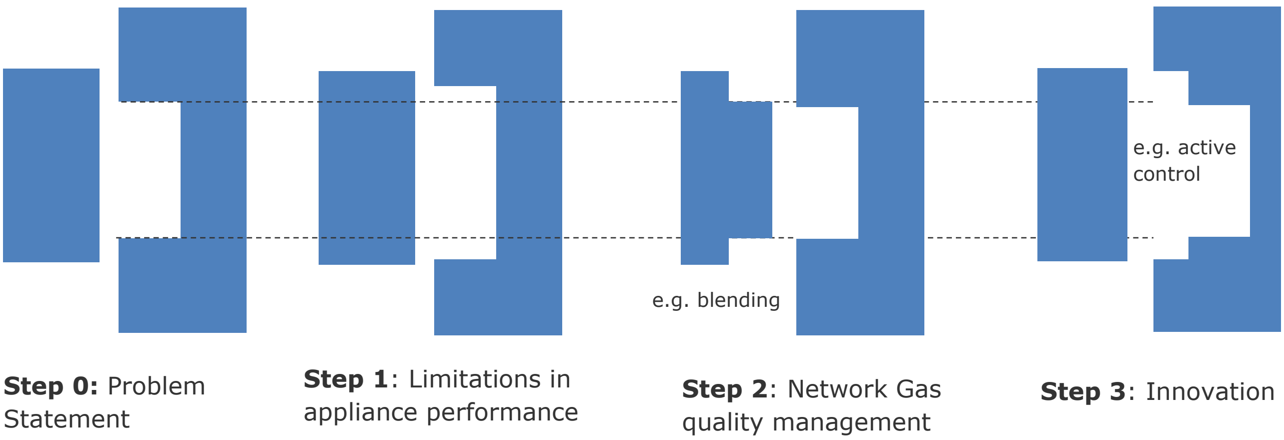

Figure 1: Schematic representation of the project approach

We briefly elaborate the steps in the approach further below.

Step 1 - Limitations of appliance performance

As mentioned above, at present it is unclear what the range of gases is that can be accommodated by GAD appliances. In this step we assess the range of gases that the current E/H-band appliances can accept. To do so, we critically review experimental laboratory results, theoretical analyses and factual field experience. Among others, we use field/laboratory evidence from the United Kingdom, Germany, Belgium and Denmark.

Step 2 - Network operator gas-quality management

Possible restrictions placed on gas composition by appliance performance can be mitigated by (centralized) gas treatment in the gas transmission network. These measures are evaluated in this part of the analysis. The key question in this step is to assess what the technical feasibility and potential costs involved are in controlling the range of gas compositions.

Step 3 - The pros, cons and costs of innovation

As a third step, the impact of innovation on the quality range gas appliances can accommodate is assessed. Innovations could make appliances more robust towards variations in gas quality. This step provides insight in the impact of current and expected innovation on the possibilities to widen the acceptable range of gases.

1.2 Structure of this report

The next chapter of this report provides the assessment of the possible ranges of gases accommodated by the appliances based on current approval regime. In Chapter 3, the network view on gas quality management is given. An assessment is provided of the possibilities for, and costs of, treating the gases to limit their range, including developments in the local gas market, specifically regarding (changes in) the so-called small fields. Chapter 4 gives an overview is given of appliance innovations which could help making the domestic appliances more robust towards variations in gas quality. And, finally, Chapter 5 forms the synthesis of the analyses in the other chapters, and gives recommendations regarding the gas quality band for H-gas to be used in future.

2 LIMITATIONS OF APPLIANCES

The task at hand is to advise the Dutch government in choosing a range of gas compositions that will provide the fewest restrictions in supply while maintaining the levels of safety and reliability for the end user with the lowest (social) cost. To achieve this, the range of gases that are accepted in the system and the performance of appliances must be matched, and possibilities for treating gas exploited. The following steps are followed to assess the range of gases that the current E/H-band appliances can accept.

- Critical analysis of existing data from laboratory experiments on appliances or from well-defined field tests.
- Critical analysis of non-experimental information: theoretical studies
- Critical analysis of evidence-based 'experience'

2.1 Background

The scheme in EN 437 to categorize appliances places E/H-band gas appliances in the generic categories I_{2E} or I_{2H}. In EN 437, the gas compositions used to test the new appliance are defined. The test gases consist of a reference gas (G20 for E/H appliances) and extreme limit gases (ELGs, whose composition depends on whether the appliances are E or H band).

The tests are performed by certified bodies and performed at reference operating condition (20°C and 50% relative humidity) and at reference installation conditions. Four different ELGs are used in the tests, each of them describing a specific combustion risk:

- Incomplete combustion and soot limit gas
- Light back limit gas
- Flame lift limit gas
- Overheating limit gas, which is only specified for certain type of appliances

In Table 1 the reference gas and the four ELGs for the H-group are presented.

Table 1: Characteristics of the test gases for the H-group

	Wobbe index, MJ/m^3 (15, 15°C)	Wobbe index, MJ/m^3 (25, 0°C)
Reference gas, G20	50.72	53.47
Incomplete combustion & sooting limit gas, G21	54.76	57.73
Light back limit gas, G222	47.87	50.46
Flame lift limit gas, G23	45.66	48.13
Over heating limit gas, G24	52.09	54.91

The ELG tests are designed to guarantee that none of the combustion risks described above will occur during operation with normal variations in gas composition within the lifetime of the appliance. Here we emphasize that the ELGs are not the allowed distribution gases; the purpose of ELGs is to provide a safety margin for the operating conditions, for example variation in the ambient conditions such as humidity and air temperature that affect the combustion performance and a range of varying installation conditions (incorrect settings, some drift of the settings, some wear, tear and fouling of components) that the appliances face in the field. Clearly, these conditions may differ from those used in the approval tests.

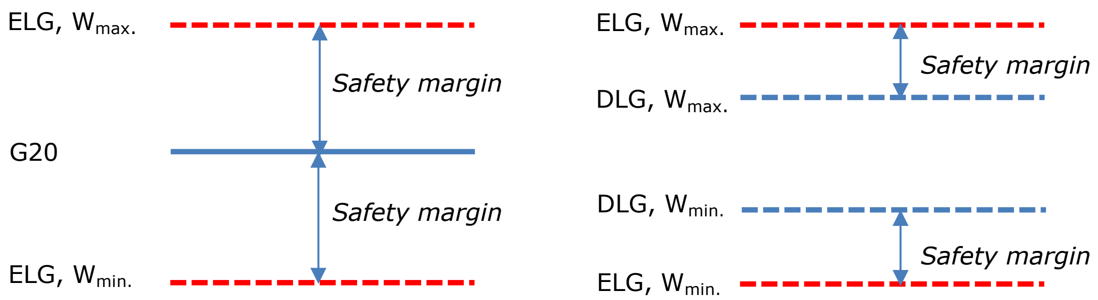

Figure 2a, Left: schematic illustration of the safety margins and test gases defined in EN 437
Figure 2b, Right: schematic illustration of the safety margins, ELGs and DLGs

Since the reference test is performed with pure methane (G20), the ELG safety margins are relative to G20 in the tests; this situation is illustrated schematically in Figure 2. The norm EN 437 does not define which distributed range of Wobbe index and gas composition is covered by the ELGs. Therefore, the actual distribution ranges and the relation between the ELGs and the range of distribution gases whose safe use is guaranteed by the ELGs (specified by 'distribution limit gases', DLGs) are neither defined nor discussed. The key question is which ranges of gas composition, illustrated in Figure 2b, do the requirements in the Gas Appliance Directive guarantee for appliance category I_{2E}?

Two complications must be considered when discussing safety margins as illustrated in Fig. 2:

1) Different combustion risks may entail different safety margins; thus, for a certain class of burner configurations (so-called Bunsen-type flames), the safety margins for flashback or flame lift, both of which are risks at the lower end of the Wobbe range, can be different.
2) While distribution ranges are traditionally given as a range of Wobbe Index, compositional effects must also be considered. In addition to the necessity of weighing the effects of different combinations of non-methane hydrocarbons, the effects of components such as hydrogen and CO_2 are not considered in the methodology.

These aspects are considered at length in the KIWA study [1].

It should be emphasized that harmonization of the categories of gas appliances under the GAD by no means implies that the actual range of gases that can be distributed is harmonized. The lack of agreement among the EU member states regarding a harmonized standard for Wobbe Index under CEN Mandate M/400 attests to this remark. When consenting to the GAD the member states only assented that the appliance approval regime was considered adequate for the *established distribution practice* in the different countries [2]. There is no theoretical or mathematical basis for the relation between range of ELGs and the distribution range of ELGs guaranteed by the GAD, each country made this decision based upon its own experience and practice.

2.2 Critical analysis of existing data from laboratory experiments on appliances or from well-defined field tests

In this section we provide an overview and critical analysis of reports which are based on data from laboratory experiments. We discuss the following published major experimental studies:

- GASQUAL, including the Spanish study on central heating boilers
- UK gas quality exercise
- Additional experimental studies (GTS field monitoring)

We provide a critical analysis of these studies in separate sections below.

2.2.1 GASQUAL

The largest study performed for H/E-band appliances was the GASQUAL study [3]. This study was performed by a consortium of laboratories and research institutes under the EU mandate M/400 on gas quality, supervised by CEN TC 234. In this experimental study, more than 100 (with few exceptions, new) appliances in 29 different categories were tested under laboratory conditions for their response to variations in gas quality. The GASQUAL experimental study was limited to domestic appliances, and did not include GAD appliances intended for industrial or commercial. To analyse possible trends, the range of gas compositions extended beyond the ELGs given for H gases in EN 437. An important point in the treatment of the data was that a worst-case approach was taken: if multiple appliances were used in one category, then the performance of the appliance with the worst response to variations in gas quality was taken as being representative of the whole category. It was argued that while many other (new) appliances would/do perform better, there will also be appliances installed in practice that perform more poorly. All GASQUAL experiments were performed under (otherwise unspecified) laboratory conditions.

Based on a weighting scheme in which the numbers of appliances per category installed in the EU were considered, conclusions were drawn regarding the numbers of installed appliances that could accept a given range of gas quality. The study assumed that there were 192 million domestic appliances intended for the H-band distribution gases installed in the EU. Thus,

- "10 M(illion) have issues all over the Wobbe range" (these are adjustable lean-premixed boilers that have been adjusted for the local gas quality),
- "183 M(illion) can cope with a Wobbe Window 46 to 50.8 MJ/m3" (15/15),
- "96 M(illion) can cope with a Wobbe Window 46 to 54.7 MJ/m3" (15/15).

Here, 'can cope' means that there were no performance issues for all categories (when considering new appliances). For appliances for which performance issues meant an increase in CO emissions, 'can cope' meant that the increase in CO emissions relative to the 'reference gas' (generally G20) was less than 500 ppm[1]. Thus, by implication, 87 million appliances develop performance issues (i.e., an increase in CO emissions of 500 ppm or more) between 50.8 and 54.7 MJ/m^3 (15/15), thus between 53.5 and 57.6 MJ/m^3 (25/0). The analysis also shows that the combination of gas quality and increased supply pressure raise caution regarding instantaneous hot water heaters. Note that the class of adjustable (modern lean-premixed) appliances were adjudged to perform well when properly adjusted.

While the report itself discusses a number of limitations regarding the conclusions of the report, there are two aspects that are worth recalling in the context of the current report.

[1] While an increase of less than 500 ppm CO when changing gas composition was considered as an inconsequential impact of gas in the GASQUAL study, independent of the initial CO emission, this choice of interpretation is not undisputed (see UK study below).

- First, as discussed in the report, nearly all the appliances tested were new. It is thus not possible to translate the impact of the same gas quality variations on the actual population installed in the field, with all the variations in installation and maintenance regime.
- The second aspect that was briefly discussed in the report was that of the variations in weather conditions; while the GASQUAL report asserted that "…the probability of all parameters having an influence (gas pressure, voltage, ambient, temperature, ambient pressure, Wobbe) are all varying at the same time in a way to increase the CO is of course small…"(Ref.[3], p.89), the possible effects were not quantified. As discussed below, the variation in ambient conditions can have a large impact, and are additive to those caused by changes in supply pressure, for example.

Discussion regarding maintenance regime and relation with Repsol study:

To relate the measurements on new appliances to the situation in the field, the GASQUAL report made a connection between the performance of new appliances and maintenance regime. There it was asserted that maintenance according to the manufacturers' instructions results in appliance performance resembling that of the new appliance, and thus the results of the study are applicable to the installed and maintained base of appliances. That is, according to the GASQUAL criteria, appliances that showed 'no impact of gas quality' when new would also show no impact of gas quality when maintained. In the GASQUAL report [3], reference is made to a study performed by Repsol [4]. In this study, 8 (purportedly non-GAD) appliances were taken from the field and examined in the laboratory. While cleaning the appliances resulted in low CO emissions of 6 of the appliances (<100 ppm dry, air-free for all 6, and <20 ppm for 5 appliances), even when tested with G21 at 25 mbar, 2 of the appliances still had relatively high emissions (953 and 1427 ppm, increases of factors of 20 and 28 compared to the CO emissions when supplied with G20, respectively) under these conditions. Using the same GASQUAL criteria, these two appliances demonstrate either 'moderate impact of gas quality' (increase of more than a factor of 2 in CO emissions but with emissions below 1000 ppm) or 'high impact of gas quality' (increase of more than a factor of 2 in CO emissions and with emissions above 1000 ppm). Thus, according to the GASQUAL criteria, maintenance failed to return these appliances to the state of 'no impact of gas quality', casting doubt on the efficacy of maintenance at restoring appliance performance to that of new appliances showing no impact of gas quality.

In addition, as mentioned above the GASQUAL study points out that the lack of maintenance can result in substantially poorer performance than that observed for new appliances.

We point out here that, in general, manufacturers' instructions for maintenance do not include insuring that the performance is 'as good as new'. Guaranteeing such performance as a prerequisite for safe use of a wide range of gas compositions implies mandatory maintenance of all appliances, both with new manufacturers' instructions and potentially increased costs to restore 'new' performance.

<u>Key conclusions derived from GASQUAL</u>

- Based on the laboratory tests performed for H/E-band appliances by the consortium of laboratories, under the assumption that all appliances in the field would be maintained to perform as new appliances, it was estimated that:
  - 10 million of the installed appliances have issues all over Wobbe band
  - 183 million can cope with a Wobbe Window 46 to 50.8 MJ/m3 (15/15)
  - 96 million can cope with a Wobbe Window 46 to 54.7 MJ/m3 (15/15)
  - Local adjustment of 'adjustable' appliances with a gas towards one extreme of the Wobbe band results in diminished range at the other end of the Wobbe band. Partially

premixed burners, particularly hot water heaters and radiant 'fires', have issues regarding unwanted increases in CO emissions at the higher end of the Wobbe band.

- This estimate neglects the effects of ambient conditions and the lack of maintenance in the field, while the assumption that maintenance restores equipment to 'new' performance showing no impact of gas quality has not been supported unequivocally.
- Since variations in installation, maintenance and weather rarely combine to improve the performance of installed appliances when compared to the laboratory, conservatively, we see no reason to view the GASQUAL results as being more 'worst case' than what could be expected in the field.

2.2.2 Laboratory Experiments in the UK Gas Quality Exercise

In 2003-2007, the UK government (at that time, the Department of Trade and Industry, DTI, later BERR, Business Enterprise and Regulatory Reform) assessed the challenges of changing gas quality [5], motivated by the increased import volumes of natural gas from varying sources and EU activities related to gas quality, such as the EASEE-Gas development and discussions in Madrid Forum. This assessment took the form of a public consultation with stakeholders; in addition, a number of projects were specifically commissioned to address individual aspects. Three studies were performed to examine the performance of H-band appliances, taken from the field and measured in the laboratory [6, 7 and 8]. In one study [6], 4 appliances were non-GAD appliances with one GAD condensing boiler. The other two studies, performed by different laboratories each used (different sets of) 10 GAD appliances, chosen to reflect the variety of appliances installed in the UK. These included conventional and condensing boilers, gas cookers and ovens, radiating tile heaters and live-action fires. Each of the studies subjected the appliances to a wider range of gases than indicated in EN 437, to capture potential trend information. Since the methodology behind the UK regulations, the Gas Safety (Management) Regulations, the GS(M)R [9], considers potential nitrogen ballasting, high-Wobbe gases ballasted to GS(M)R specifications were also included in the studies. Studies [7] and [8] used the same gas compositions in the experiments.

After receipt of the appliances from the field, they were tested with G20 to assess their condition relative to the installation/certification requirements and subsequently serviced according to the manufacturers' instructions. Restricting the scope to CO emissions (other operability issues were also studied), the results of the studies are illustrated by a short list of quoted conclusions, note that the Wobbe Index is given at (15/15) conditions:

- "The results have conclusively shown that broadening the UK's gas quality limits outside the current GS(M)R specification (51.41 ≥WN≥ 47.20 MJ/m^3), particularly by increasing the Wobbe Number, would have implications for NOx and CO emissions." [8]
- "Generally the test gases within the range of Wobbe Numbers from 45 to 52 MJ/m^3 resulted in acceptable appliance operability compared with current standards for G20 reference gas. The exceptions to this general trend were the cooker hob burner, condensing boiler 1 and the LFE fire which all had CO emission problems over a wider range of gases." [6] and
- "Increasing the Wobbe Number of the gas used will almost certainly increase the emission level of carbon monoxide. Whilst the levels produced from the appliances tested here were on the whole modest, except for Wobbe Number gases >53 MJ/m^3, there is the potential for badly maintained or installed appliances to produce CO levels that may cause an increasing overall health risk." [6]

While both studies showed that maintenance following the manufacturers' instructions generally resulted in improved appliance performance, a number of exceptions were also seen in which post-maintenance performance was worse than pre-maintenance. Comparison of the results with the UK installation guidelines (limit for mandatory maintenance at $CO/CO_2 < 0.004$; unsafe limit $CO/CO_2 < 0.008$) showed that post-maintenance performance would have necessitated action by an installer, even when fired with gases within the GS(M)R. Presuming that new appliances do satisfy these requirements, these studies cast serious doubt on the GASQUAL assertion, reported above, that maintenance according to the manufacturers' instructions results in 'as new' performance.

The Gas Quality Exercise considered the possibility of extending the range of gases to be distributed to the installed population of end-use equipment, of which domestic appliances are the dominant fraction. Although this study considered small numbers of appliances (in total 25 appliances, of which 21 GAD appliances) in comparison with GASQUAL, it had the advantage of using appliances that were taken from the field rather than new. In this fashion the deterioration in performance resulting from normal wear and tear could illustrated (albeit not with statistical significance), which was a criticism of GASQUAL. However, here too, only (unspecified) laboratory conditions were considered in the experiments, without the opportunity of incorporating the effects of ambient conditions in the analysis based on systematic observations. At the same time, the UK studies do illustrate that laboratory conditions and maintenance are no guarantee that all the H-band appliances studied can accommodate a wider range of gases than specified in the GS(M)R.

<u>Key conclusions derived from the laboratory studies performed during the UK Gas Quality Exercise:</u>

- For the H-band appliances studied, extending the range of gas qualities outside that specified by the GS(M)R (51.41 - 47.20 MJ/m3 (15/15) or 54.19 – 49.75 MJ/m^3 (25/0), will result in diminished performance, particularly regarding CO emissions. For appliances at the edge of safe performance, this diminished performance can result in exceeding the limit.
- In contrast to the assumptions made in GASQUAL, maintenance according to the manufacturers' instructions is not a guarantee for 'as new' performance showing no impact of gas quality.

Note regarding the framework of interpretation relevant for the comparison between GASQUAL and the UK exercise: In the interpretation of the results of GASQUAL and the UK exercise, it is important to consider the intention behind the studies, particularly regarding safety. In the GASQUAL report it is stated, "We don't want to say if it is safe or not, only if gas quality variations have an impact on safety." [3, p. 28]. On the other hand, the UK exercise was intended to assess whether the end user faced an increased risk as a result of changes in gas quality. In our opinion this difference is also a contributing factor to the different positions in the EU. That is, despite the results of GASQUAL described above, there is a position supporting the EASEE-Gas range as a Wobbe standard in prEN 16726, while the conclusion of the UK Consultation [5] was that, among other considerations, the increased risk for the consumer requires large-scale conversion of appliances to accommodate gas compositions outside the current GS(M)R. While neither study was intended to test the adequacy of the ELGs in EN 437, both studies impact the assessment of which range of gases is safeguarded by the generation of GAD appliances examined.

2.2.3 Experiences with non-domestic equipment: gas fired heaters used in non-domestic premises

The German manufacturers of decentralized gas fired heaters used in non-domestic premises, organized in 'Figawa' (through the committees "Gas-Infrarot-Strahlungsheizung" GIS and "Dezentrale Lüftungssysteme" DLS) studied the effects of qas quality variations on non-domestic gas fired heating appliances and used the results as input for the European GASQUAL study [3]. In this so called "Figawa" study, laboratory experiments have been performed by the manufacturers and the field experience of the participating manufacturers regarding on-site adjustment, wear and tear etc. were taken into account. While the age of the appliances is unknown, the appliances were tested using three gases, G20 and two GASQUAL test gases, at 45,66 MJ/m³ (25/0) and 55,26 MJ/m³ (25/0). The types of gas-fired heaters studied were considered to be representative of those installed since 2000, and were categorized as follows:

- Warm Air Heaters / EN 1020, EN 1196
- Radiant Luminous Heaters / EN 419-1
- Radiant Tube Heaters / EN 416-1, EN 777-1…4

It was concluded in Ref. [10-12] that "Variation of natural gas quality in a range between 45,66 MJ/m³<Wo<55,26 MJ/m³ (25/0) shows significant problems in safety, combustion and lifetime in the performance of gas fired decentralized heaters in non-domestic premises." Specifically, depending on the appliance type, most of the deleterious effects were observed at the highest Wobbe Index (as compared to the performance when using G20), including substantial increases in CO (and NO_x) emissions, overheating of heat exchangers and other performance issues. Thus, the study concluded that the free variation of gas quality within this range was unacceptable for a satisfactory performance of installed as-fired heaters.

The official position of the French organization of manufactures of gas fired heaters, CER [13] is consistent with this conclusion, stating that local Wobbe index variations greater than 4.22 MJ/m^3 should be avoided. This maximum Wobbe band is based on French experience, in which no variation greater than 4.22MJ/m^3 was reported in the field by CER members[2]. Of course, this does not mean that variations larger than 4.22 MJ/m^3 will result in malfunction, but only that the response of installed equipment for larger variations in Wobbe Index is unknown.

The organizations FIGAWA, ELVHIS and EURO-AIR also strongly support the CER position Ref. [11, 12] with regard to the maximum recommended range of 4.2 MJ/m^3.

Recently DNV GL, on behalf of Gas Transport Services (GTS), studied the effects of Wobbe variation on the (safety) performance of a radiant burner used for indoor space heating that was installed in the H-gas grid and connected to a 1 baro supply pressure [15]. The burner used was taken from the field and tested the DNV GL laboratory according to the NEN-EN 419 procedure. The test gases as defined in the EN437 for the family 2H were used in the tests. During the measurements no flash-back, flame-lift or soot formation occurred. Moreover the CO fraction during all experiments was lower than 205 ppm. The measured radiant intensity decreased almost linearly with the Wobbe Index (i.e., proportional to the thermal load), with a maximum reduction of about 18.5% when using G23 instead of the reference gas G20. It was concluded that this particular radiant burner taken from the field can safely operate within the Wobbe range (48.3-55.7MJ/m^3, 25/0) at the (ambient) conditions used in the tests. Since no effects of varying ambient conditions were considered, the range of gases was different and only one radiant burner was tested, it is impossible to compare this result with the Figawa study, and is imprudent to generalize this result. However, the results of this study do not contradict those of the Figawa study nor

[2] This range of distribution gases in France was also reported in ref. [14]

of the French experience, in which a maximum variation in the Wobbe Index of distributed natural gas of 4.22 MJ/m^3 is recommended for this type of burner.

Key conclusions:

- Laboratory studies performed by manufacturers indicate that the range of Wobbe Index 45,66 MJ/m³ - 55,26 MJ/m³ (15/15) is unacceptable for a satisfactory performance of installed non-domestic gas fired heaters.
- A number of European manufacturers' organizations support a maximum range that is limited to 4.22 MJ/m^3 for satisfactory performance of their equipment in the H-band of natural gas.
- Experiments on a specific radiant burner taken from the field show safe performance over a band Wobbe range of 48.3-55.7MJ/m^3 (25/0). The radiant intensity decreased almost linearly with the Wobbe Index

2.2.4 Experiments on non-domestic MW-scale burners for industrial and commercial heating

In the framework of the EDGaR research program, an experimental study was performed by DNV GL [16] on 4 modern low-NO_x burners intended for use in a boiler for hot water (falling under the GAD). The performance of the burners regarding flame stability, flame length and CO/NO_x emissions was assessed for a range of H-gases, 48.3 MJ/m^3 – 57.2 MJ/m^3 (taken at 25/0), slightly wider than the EASEE-Gas range. The experiments were also performed at high, intermediate and low load, in keeping with the use of the burners in practice. The purpose of the experiments was to see whether the burners could accept the EASEE-Gas range without significant loss of performance, explicitly including the effects of air ratio adjustment at the extremes of the range, which can occur if the gas quality upon adjustment is not known. Assessing the adequacy of the approval regime was not the goal of the study.

The results obtained are reminiscent of the GASQUAL results for adjustable lean-premixed domestic appliances. Focusing on flame stability and CO emissions, under the (laboratory) conditions of the experiments, adjustment in the middle of the range of gases ensured adequate performance across the range, when the setting of the load (high, intermediate, low) was kept constant. However, adjustment at the extremes of the range led either to unacceptable increase in CO emissions (adjustment at low Wobbe) or to flame instability, and even to blow-off (adjustment at high Wobbe). An important observation is that when the load setting was varied, hysteresis in the air ratio controls of 2 of the burners limited the acceptable range of Wobbe Index to ±5% (a band of roughly 10 MJ/m^3), even when using central adjustment. The study concluded that increasing the range requires some form of active control, which will be discussed under 'innovation' below.

Key conclusions derived from the experiments on non-domestic burners:

- Proper adjustment is an essential requirement for acceptable performance across a wide range of Wobbe Index, but hysteresis in the standard method of maintaining a constant air ratio during modulation can lead to variations in air ratio that limit the acceptable range to a band of roughly 5 MJ/m^3
- Active control is the method by which performance can be guaranteed.

We also remark here that the GAD testing of these burners does not involve the EN 437 test gases, but rather an in-situ testing protocol. Taken together with their limited number (in comparison with domestic equipment) and the fact that these appliances also have significantly different practical requirements (such as NO_x emissions) and installation and maintenance regimes, we are disinclined to consider them in the same context as the domestic appliances. We shall return to this point in Chapter 5.

2.2.5 GTS field experiments

Recently, at the request of GTS DNV GL performed flue gas emission measurements at four H-gas locations where different boiler types are installed. In the tests, the fuel composition and the Wobbe index were measured while at the same time the CO, NO, NO_2, CH_4 and O_2 fractions in the exhaust of the boilers were monitored with a time interval of 10ms for a period of roughly 7 days. At three of the four locations the measured Wobbe fluctuations were smaller than 3.3 MJ/m^3, while at one location the measured Wobbe range was 7 MJ/m^3 (47.2-54.2 MJ/m^3). Only modest emissions of CO and CH_4 (<30 ppm CO) were measured during normal operation for all boilers monitored, indicating low emissions for these boilers over the measured ranges. Here we remark that the only boiler that was subjected to relatively large changes in the Wobbe index (7 MJ/m^3) was fed with indoor air and thus was not exposed to a wide range of ambient conditions.

The small number of appliances, the brief duration of the tests and the modest variation in range of conditions across these appliances preclude generalization of these results.

2.2.6 Manufacturer's Field- and lab-test experience with cooking hobs

One of the type of gas burners used for cooking appliances are hob burners. For these gas burners, atmospheric burner technology is applied. It is a straight-forward technology that requires no electronic control, although in some cases a thermocouple is required for a safety valve. For the burner performance, atmospheric burners use the impulse of the gas flowing through an injector and mixing air with the gas jet into the Venturi.

Interviews with a large manufacturer of hob burners falling under the category I_{2E} report that experiments performed on these burners show that they are robust, and operate safely at the ELGs of group E described in the EN 437. According to the manufacturer the largest safety margin consumed by cookers is by the production tolerances. The manufacture reported that his most sensitive cookers are the newest generation of wok burners. This manufacturer further reported that tests show that the maximum Wobbe distribution bandwidth for these burners is roughly ±5 MJ/m^3. In Belgium, where large numbers of these burners are installed, and where over the past 10 years the Wobbe Index distributed ranges from about 47.5 and 52.5 MJ/m^3 (15/15), no problems with hob burners have been reported from the market, suggesting that these cookers can cope with Wobbe variations of at least ±2.5 MJ/m^3 in the field.

2.3 Critical analyses of non-experimental information

2.3.1 KIWA study on safety margins using current ELGs

Recently, KIWA performed a theoretical study [1] to estimate the range of suitable gases for I_{2E} appliances, given the ELGs given in EN 437, based on a combustion analysis for various appliance designs. It is outside the scope of the current study to critique the results from [1] in detail, and here only the main points will be discussed. The model uses an idealised description of various configurations of the gas mixer and the burner. The study shows how much of the safety margins created between the ELG gases and G20 is actually necessary to account for changes in ambient conditions (Figure 3), wear and tear, production tolerances etc. that appliances face in the field. To make the results more accessible, the safety margins are expressed in the Wobbe index relative to methane (G20). The study shows that, for several installation variants studied, there are combinations of production tolerances, wear and tear, ambient conditions, adjustment, etc. for which the safety margin between the ELG and G20 are completely consumed. That is, for these combinations of conditions the ELGs do not guarantee the safety of the appliance even when fuelled with G20. The study further concludes that, for substantial fraction of the appliances studied, the distribution Wobbe range is limited to only a few percent, for example from -4 to +0% relative to G20. Major reasons that the ELG gases, which were designed to account for a range of natural gases for the major appliance types in existence around 1990, are no longer appropriate are the introduction of new appliance types with significantly difference combustion characteristics, such as modern lean-premixed appliances, and the wider variety of gas compositions for which the ELGs are not designed. The study recommends that more robust ELGs and/or test conditions be designed to guarantee a wider distribution range. Also recommended is that the presence of the so-called exotic components (such as ethane and hydrogen) in natural gas, which limit the distribution range further, should also be taken into account when designing new limit gases/conditions.

Without assessing the correctness of the computed safety margins for each of the appliance classes considered, a question that is posed to policy makers when following this methodology is the extent to which all cumulative negative effects, i.e., the extreme 'worst case', should be considered as the rule for determining the safety margins. One question in this regard is whether the confluence of the maximum limiting effects is realistic or 'simply' conservative. Part of the answer lies in the occurrence and duration of 'extreme' conditions, and of course in the consequences for the end user, similar to arguments regarding the use of an 'emergency limit' in distribution standards. Practical experience, as discussed above, suggests that the safety margins may be larger, possibly due to a larger 'informal' safety margin as indicated in [1]. At the same time, quantification of the informal margin can only be determined empirically. Another question regards the desirability of using G231 as the lower limit of the E band, which may flatter the possible range of DLGs at lower Wobbe Index. Examination of EN 437 suggests that appliance use is intended for adjustment with G20 for W>G23 and with G25 for W<G26. It is unclear how to translate the assessed safety margin to the H-range of gases. However, the methodology applied in the study provides a rational framework for assessing the relation between the safety margins and the ELG tests.

Despite any possible conservatism in the estimates presented in [1], the results show that the premise used in the range of gases put forward in the EASEE-Gas Common Business Practice [17] (Wobbe range 47-54 MJ/m^3, taken at 15/15, which is the basis for the CEN M/400 activities) is flawed. One of the major contributors that limit the Wobbe distribution band is the variation in ambient conditions (pressure, humidity and temperature). For example, the calculations presented in [1] show that variations in ambient conditions consume roughly 15.0% (-8.3% to +7.3%) of the Wobbe safety margin for Bunsen-type appliances (e.g. cookers) in the worst case situations. DNV GL performed calculations for the same appliance type and conditions using an independent methodology and observe that variation in weather conditions consumes 12.5% (-8.6% to +4.1%, based on flashback and incomplete combustion) of the Wobbe safety margin. Both calculations indicate that significant fractions (for the H range, 50% or more) of the safety margins are consumed by variations in ambient conditions. In one of the Marcogaz position papers [18] a simple analysis was performed to estimate the changes in air ratio with varying weather conditions, yielding an equivalent variation in Wobbe Index of ~10% for the H-band. However, that document fails to relate those changes with the safety margin. Applying an estimate of ~10% consumption of the safety margin by ambient conditions to the H-gas range (as intended by EASEE-Gas) shows that a distribution band of at most ~4.5 MJ/m^3 seems warranted, consistent with the traditional distribution ranges reported one of the Marcogaz documents [19].

Additionally, an independent combustion analysis by DNV GL (then Gasunie Research) was presented at a meeting of CEN TC 238 (regarding EN 437) in 2006 [20] of the adequacy of the ELG for flashback (G222, 23% H_2 in methane) as a limit gas for modern lean-premixed appliances. Since the air ratio becomes leaner with hydrogen addition, for lean-premixed equipment without active air ratio controls the hydrogen addition to methane actually lowers the burning velocity, rather than increasing it. Thus, G222 in these appliances has a lower burning velocity than pure methane, G20. It was demonstrated that for this class of appliances the ELG for flashback does not test for flashback. In reality, high-Wobbe gases increase the risk of flashback and/or burner overheating. The inefficacy of G222 and the lack of use of G24 in approval procedures [1] mean that there are de facto no tests that safeguard these appliances for flashback and overheating for natural gases.

Key conclusions derived from the KIWA analysis:

- The safety margins between G20 and the ELGs are limited. For several installation variants studied the ELGs do not guarantee the safety of the appliance even when fuelled with G20
- A large part of the safety margin between G20 and the ELGs is consumed by changes in ambient conditions
- The current set of ELGs and/or test conditions do not safeguard the performance of (modern) appliances for a wide distribution range (consistent with the EASEE-Gas CBP) including the presence of the so-called exotic components.

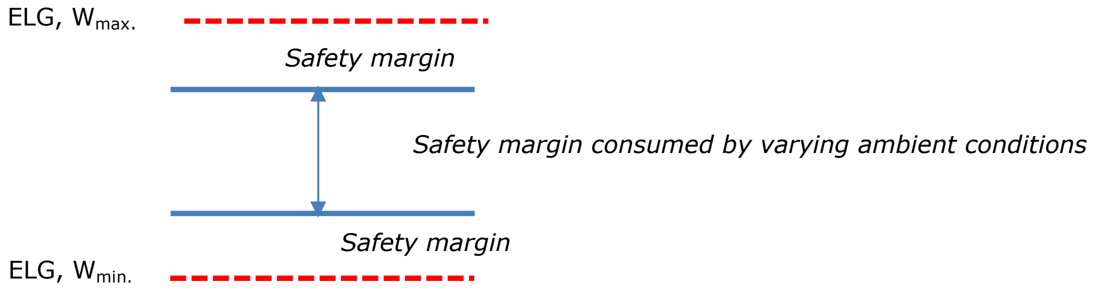

Figure 3: Schematic illustration of the safety margin consumed by varying ambient conditions

2.4 Experience in different countries

Below is a synthesis of the experience in different EU countries, based on interviews and public documents, including the response of different countries to the proposed Wobbe range in the CEN M/400 exercise.

2.4.1 Denmark

The Danish respondent reported that a specific issue was that there are essentially two different ranges of gas quality, lean Russian gas from Germany and relatively rich Danish gas; the gas actually distributed can change, without the gases being blended. The main issues have been operational issues with boilers that were adjusted to Danish natural gas at the installation stage, and then were supplied with gas from Germany. It was decided to readjust all appliances to the original setting (G20). Towards this end a large education action was undertaken toward installers.

The respondent also reported that since 2012 there are new official gas quality standards in Denmark "Gasreglementet afsnit C-12 Bestemmelser om gaskvaliteter (14. december 2012)". According to these rules, under "normal conditions of distribution" the Wobbe range is defined between 50.76 - 55.8 MJ/m_n^3 (25, 0). There is also an "exception" distribution limit (apparently an emergency limit) in which the Wobbe Index can also be between 50.04 and 50.76 MJ/m_n^3. Denmark has a mandatory maintenance for all open-flue appliances, to be performed every 2 years.

The defined Wobbe range in Denmark is mainly based on a consensus in the gas industry, which considers the gas distributed, including new gases on the Danish market, and the existing knowledge on impact of gas quality on various utilization (tests in laboratory, feedback from the market, studies, etc.). We observe here as well that information provided in GASQUAL shows that the variation in installed appliances is limited, being mostly adjustable premixed boilers and cooking burners. The instantaneous hot-water heaters, shown in GASQUAL to be sensitive to high-Wobbe gases, have a very limited presence in Denmark.

Key conclusions:

- The Wobbe range in Denmark is defined between 50.76 – 55.8 MJ/mn^3 (25, 0), substantially more narrow than the EASEE-Gas proposal.
- Re-adjustment of appliances was necessary in Denmark due to a change in gas quality.

2.4.2 Germany

In Germany, E band appliances are installed in the H gas areas.

Based on information obtained in GASQUAL and on interviews, the installation practice in Germany is to adjust the appliance for maximum performance: emissions, thermal input and efficiency. Thus, in a region having (relatively) low-Wobbe gases, the burner pressure is increased to maintain thermal input, and for appliances having adjustable fuel-air ratio, this is also adjusted to minimize pollutant emissions and maximize efficiency, again using the local gas. As indicated in GASQUAL, this situation limits a country-wide extension of the *distribution* range of natural gases.

The H-gas distribution range is defined in the DVGW-Arbeitsblatt G260. According to the G260 the Wobbe index in the H-gas band is 54.0 MJ/m3 (25, 0) and the allowed bandwidth is +2.5/-5.0 (49-56.5 MJ/m^3). However, the actual local variation in Wobbe Index in Germany is limited to about ±1 MJ/m^3 Ref. [3, 21]. Interviews with manufacturers indicate that variations outside this range results in performance issues, particularly regarding CO emissions; this requires readjustment when the local gas quality changes outside this range (based on the experience of the manufacturer). The relative small fluctuations in Wobbe Index distributed are partially a consequence of the strict requirements imposed on the allowed variations in calorific value that is needed for the billing of the natural gas. As stated in the Code of Practice G 685 'as a general rule, the billing calorific value of an individual exit point shall be determined on the basis of its geographical location. The billing calorific value shall not deviate by more than 2% from the mean calorific value of the gas supplied over the billing cycle'. The German network operators are able to maintain this narrow bandwidth because the supply mix of gas in Germany is less diverse compared to the situation in the Netherlands. H-gas to Germany is predominantly supplied from Norway and Russia.

Contact with a large German manufacturer indicated that a process has been initiated to change this situation. During the next few years, the actual tolerances of field-installed equipment are to be evaluated, and steps towards increasing the distribution band (to be taken over a long period) are then to be decided. This process resembles the current Dutch 'transition'.

2.4.3 UK

As discussed above, the limits on the distribution band in the UK has been set legally in the GS(M)R since 1996. As illustrated in Marcogaz documentation [22] nearly the entire band is factually used in distribution, and the conclusion of the UK Gas Quality Exercise was that this band was not to be widened. Recent information indicates that the same wide range is being distributed. While there are regional differences, depending on the proximity of individual consumers to entry points in the grid, no provisions are taken to allow for a smaller band. Appliances are not normally to be adjusted for the local gas quality. Recently, due to a 'small number of incidents' regarding undesired CO emissions from some lean-premixed boilers, an additional instruction has been given to installers to ensure adequate emissions from these appliances [23]. While maintenance according to the manufacturers' instructions is actively promoted in the UK, inspection and maintenance is only required for rental properties.

We also report that a study has begun in Oban (Scotland) to assess the conditions under which the band mandated by the GS(M)R can be extended. This study [24] includes an initial testing of the compliance of domestic equipment installed in the field, and possible replacement of non-compliant equipment, followed by testing of the equipment performance with a wider range of gases for a relatively large number of appliances (an initial sample of 100, followed by a larger complement of 1100 appliances). This study is intended to run to the end of 2016.

2.4.4 Belgium

The Belgian grid is made up of two systems: one for the transmission of low-calorific natural gas and one for the transmission of high-calorific natural gas. The appliances installed in the gas grid belong to the appliances categories I2E+, I2E(S), I2E(R) en I2N. In Belgium it is obligatory to perform maintenance and/or inspection for boilers. Depending upon the region in Belgium these inspections have to be performed at least once in the two or three years where the boilers must meet the set requirements in terms of CO emissions and flue gas temperature. In an ongoing review of the legislation it is under discussion to expanding/changing the legislation by including other types of devices and to set the minimum rate of maintenance and/or inspection interval in all regions to 2 years.

The respondent from Belgium reported that the Wobbe index of the gases distributed over the last 10 years in the H-gas grid in Belgium ranges between 47,5 and 52,5 MJ/m^3 (15/15). This range of distribution gases is substantially narrower than the EASEE-Gas proposal.

2.5 Inventory of 'conversion' methods in other countries

2.5.1 Germany

In Germany, when the gas composition is to be switched from L-gas to H-gas, the appliances must be physically altered. Since the current procedure includes those intended to replace non-GAD or non-compliant equipment, not considered relevant for the current study, we only report the process relevant to a changeover for E-band appliances. Based on information obtained from interviews (manufacturers and others) the gas companies in the area to be switched instruct a central authority to initiate the process of change. A central authority is used to ensure that no equipment is missed in the changeover. The parts that must be replaced (nozzles/injectors) are ordered and the process organized logistically. The costs of changeover are estimated to be ~€200/appliance. After changeover, the appliances are checked to ensure safe performance.

2.5.2 Belgium

Currently several areas, for example the harbor area of Antwerpen are being converted from L-gas to H-gas. Although the conversion procedures are not yet fully established one can make a distinction between the four different appliance categories present in Belgium; I2E+, I2E(S), I2E(R) en I2N. According to our Belgium respondent the majority of the domestic appliances installed belong to the category I2E+. For this group of appliances to convert L-gas areas to H-gas areas the supply pressure is reduced from 25 to 20 mbar. Once the supply pressure is changed the installed E-band appliances should be tested to guarantee the safety for end-users, although this is not mandatory. The costs of the conversion is estimated to be 50-70 Euro per household [25]. According to our own estimations these costs are slightly underestimated and should be in the order of 100 euro for I2E+ appliances.

A small part of the domestic appliances and the majority of the appliances with a power above 70kW belong to the category I2E(R). These appliances have a pressure regulator which should be manually adjusted when switching from L-gas to H-gas. The appliances from the category I2N have a fuel/air control system that allows these appliances to switch from L-gas to H-gas without performing any adjustments to the appliances and consequently no additional costs are involved.

For hob burners a possible future change of gas from L-gas to H-gas requires the installation of a gas conversion kit, containing the right injectors for H-gas. The costs for a conversion are estimated somewhere in the range of €100 - €200 euro according to information obtained from an interview with a hob burner manufacturer.

2.6 Summary of observations and conclusions based on earlier studies and field experience

The observations and conclusions described below are based on the review of experimental laboratory results, theoretical analyses and factual field experience. Opinions without substantial theoretical, experimental or experiential argumentation regarding the range of Wobbe Index that H-band appliances falling under the GAD can accept have not been reported. Consideration of the individual studies and field experience discussed above shows that there are few 'facts' regarding the range of gas quality that is, or can be, guaranteed by the GAD. *We have found no clear experimental or experiential evidence that demonstrates that the large-scale and long-term safety and proper performance of end-use equipment qualified under the GAD is guaranteed for a distribution band of 7 MJ/m^3 (EASEE-Gas) or wider.*

2.6.1 Experimental studies

Well-defined experimental studies have been performed on mainly new appliances, but under laboratory conditions for brief periods. This leaves the effects of variations in ambient conditions, normal wear and tear, and any potentially long-term effects on the acceptable range of gas composition uncertain, even when maintained according to the manufacturer's instructions. The observations made thus far under well-defined conditions were based on a limited number of (new) appliances and with limited ranges of ambient conditions, so that no generalized conclusions can be drawn with any statistical certainty.

- The GASQUAL study showed that even new appliances, when installed in accordance with local practice, can show safety and operational issues when supplied with gases within the H-band. Based on this study, even when adjustable appliances are adjusted correctly, the entire appliance population only performed 'without impact of gas quality' within in a range of Wobbe Index of roughly 5 MJ/m^3.
- Well-defined experimental studies (UK) have been performed on appliances taken from the field, but under laboratory conditions and for brief periods, leaving the effects of variations in ambient conditions and any potentially long-term effects on the acceptable range of gas composition uncertain. Here too, extending the range above ~4.5 MJ/m^3 was considered to result in unwanted deterioration of appliance performance.
- These studies also provide examples (UK, Spain) showing that maintenance according to the manufacturer's instructions does not necessarily result in acceptable, or even improved, performance.
- For non-domestic equipment, experiments under laboratory conditions on MW-scale modulating, low-NOx burners also indicated that, while a number of burners can accept a wider range, for some types of burner a maximum of ~5 MJ/m^3 was possible. In addition, laboratory experiments by manufacturers of local, non-domestic heating equipment indicated that a band of 9.6 MJ/m^3 resulted in unacceptable performance, but did not state what the maximum band was; a limit of 4.22 MJ/m^3 (based on field experience) was supported.

2.6.2 Theoretical analyses

The theoretical study performed by Kiwa estimates the range of suitable gases for I_{2E} appliances, given the ELGs listed in EN 437, based on a combustion analysis for various appliance designs.

- The Kiwa study (and other theoretical analyses) show that the estimate of the safety margins between the EN 437 limit gases and an acceptable distribution band used to set the EASEE-gas recommendations severely underestimate the effects of ambient conditions on appliance performance. These theoretical analyses are based, in the first instance, on the variations in fuel-air ratio caused by changes in gas quality and ambient conditions, which are supported by experimental observation.
- The study concludes that for some types of appliance, the intended safety margin, as compared to G20, becomes zero under some operational conditions.
- In general the analyses show that the current test gases in combination with the test procedures described in the GAD do not guarantee the safety for all groups of appliances. To guarantee the safety and performance for all groups of appliances it is strongly recommended to develop new test gases and test procedures.

2.6.3 Field experience

- Field "experience" based on distribution practice provides little information on the maximum range of gas composition the appliance population can accept. However, in countries having an active maintenance regime (UK, Germany, Belgium), observations of appliance performance in the field have not led to a narrowing of the existing distribution limits, such as the ~4.5 MJ/m^3 in the UK, or 5 MJ/m^3 in Belgium or more recently in Denmark. Despite uncertainties in this kind of 'field experience', these observations, with populations of tens of millions of appliances, reflect the years-long practice in these countries, with the existing safety regime; in this respect these limits may be the best reflection of what is considered acceptable given the local adjustment and maintenance custom. The distribution ranges for Belgium, Germany, Denmark, Great Britain and France are shown in the figure below. In appendix B we show examples of measured variations in gas quality as observed in Denmark, UK and France.
- Interviews and documentation indicate that the differences in distribution range considered safe are at least in part due to differences in adjustment practice. The custom in Germany of maximizing performance for the local distribution gas precludes widening the range beyond the narrow local range. In the UK, for example, in which the entire allowed range is used, there is no optimization of appliance performance for the local distribution gas. The distribution practice in the UK, Belgium, France and Denmark suggests that a band of 4-5 MJ/m^3 can be realized. We note that all these countries have some form of active maintenance regime.

2.6.4 Relevant observations of stakeholder positions

While not part of this study, we report two additional observations in passing. We observe that the lack of support of the different Member States for a wide, harmonized distribution band of gas quality in the M/400 process was in most cases based on concern for the behavior of domestic appliances.

We also report that during interviews with appliance manufacturers we inquired about the range of Wobbe Index they recommended for their H-band appliances falling under the GAD. While no experimental evidence was presented, the ranges communicated during these interviews with different manufacturers ranged from ±2% to ±7,5%, without the use of active control. These ranges depended on the type of appliance, and the adjustment and maintenance regime.

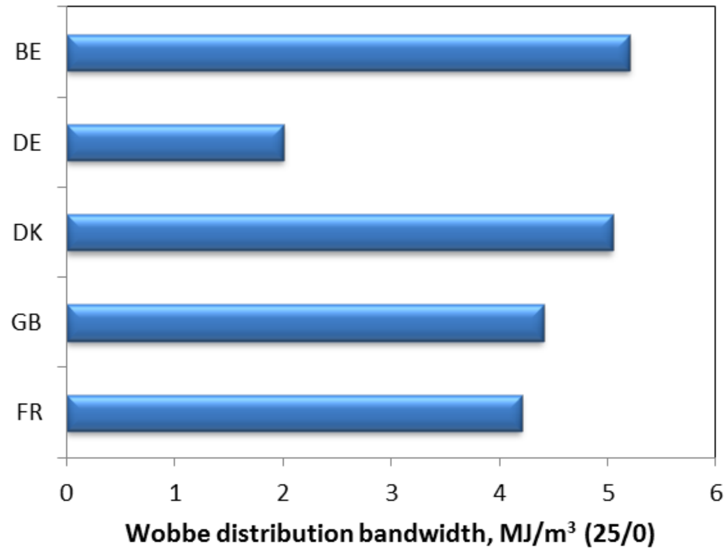

Figure 4: Wobbe distribution bandwidth for Belgium (BE), Germany (DE), Denmark, (DK), Great Britain (GB) and France (FR)

3 NETWORK GAS QUALITY MANAGEMENT

In this chapter we assess the expected gas quality bandwidth of gas that enters the high-calorific gas transmission network. The Netherlands is supplied with gas from three sources. Gas is produced indigenously from so-called small gas fields both onshore and offshore. High-calorific gas is also imported from e.g. Norway, Russia and from various other sources worldwide in the form of liquefied natural gas (LNG). And thirdly, to a lesser extent also gas is produced from renewable sources is supplied in the network.

In the previous chapter we evaluated the range of gases that can be accommodated by domestic appliances. We have found no clear experimental or experiential evidence that demonstrates that the large-scale and long-term safety and proper performance of end-use equipment qualified under the GAD is guaranteed for a distribution band of 7 MJ/m^3 or wider. At the moment the gas quality bandwidth admitted to the high-calorific gas network ranges from 47 MJ/m^3 to 55.7 MJ/m^3, substantially wider than the ranges identified in the previous chapter.

The Wobbe Index of gas produced from the ‘small fields’ is expected to be between 37 MJ/m^3 to 53 MJ/m^3 in future. The gas quality bandwidth of the gas from these small fields is thus large. In contrast, the Wobbe Index bandwidth of imported high-calorific value gas is relatively narrow: information provided by Gasunie Transport Services on the expected bandwidth of all H-gas imports expected in the future is 4.7 MJ/m^3.

In the current chapter we assess the possibilities gas quality management in the gas transmission network can provide towards maintaining the range of Wobbe Index within that potentially necessary for GAD appliances. The gas transmission system operator has basically two methods available to manage the gas quality in the system:

- Quality conversion with nitrogen ballasting can be used to lower the Wobbe Index of gas flows.
- Blending is used to inject amounts of lower Wobbe gas flows in higher Wobbe gas flows in a controlled fashion; this lowers the Wobbe Index of the higher Wobbe flow, and raises the Wobbe Index of the lower Wobbe flow.

The effectiveness of these gas quality management options are assessed in this chapter.

In the next sections we first explain the gas supply situation by showing where different gas supplies tie into the gas transmission network. Next we assess the expected development of the gas quality supplied from the various supply sources. Following that we discuss gas quality management options for handling gas supplied outside different gas quality bandwidths. The analysis is based on data and analysis provided by Gasunie Transport Services (GTS).

A recommendation for the gas quality bandwidth to be applied in the gas transmission network is not presented in this chapter. This recommendation is put forward in the next Chapter 5 – Synthesis where we balance the limitations and costs from the perspective of end-use appliances, end-use appliance innovation and gas quality management in the network.

All the Wobbe Index figures in this chapter are in (25/0).

3.1 Gas supply in the Netherlands

The gas industry in the Netherlands was sparked by the discovery of the large Groningen field. The gas from the Groningen field became the standard for the consumers in the Netherlands. It was only later that high-calorific value gas was produced from the so-called small fields in the Netherlands. Gas is also imported through pipelines from Norway via the entry point Emden, from Russia via the entry point Oude Statenzijl, from Belgium via the entry point Zelzate and from sources worldwide via the LNG terminal in Rotterdam. The focus of this study is on the gas quality requirements of H-gas. High-calorific value gas is supplied to the end users through approximately 87 connections. A separate gas transmission system was developed to accommodate these high-calorific value gas flows. The low-calorific and high-calorific systems are operated separately and are connected by means of five blending and conversion stations where high-calorific gas can either be blended with low-calorific gas streams or ballasted with nitrogen to produce low-calorific value gas for distribution.

The table below lists the entry points where gas enters the gas transmission network.

Table 3-1 Entry points in the gas transmission network

Small field supply		Groningen field	Import
1. NGT	Noordgastransport	9. Groningen	10. LNG
2. NOGAT	Northern Offshore Gas Transport		11. Emden
			12. Oude Statenzijl
3. WGT	West Gas Trunk		13. Zelzate
4. GRFR	Groningen – Friesland		
5. OM	Ommen		
6. LOCAL	JDA LoCal		
7. NH	Noord-Holland		
8. ZH	Zuid-Holland		

The figure below shows a schematic representation of the gas transmission network of GTS. In the figure we have indicated the entry points where gas is fed into the gas transmission network.

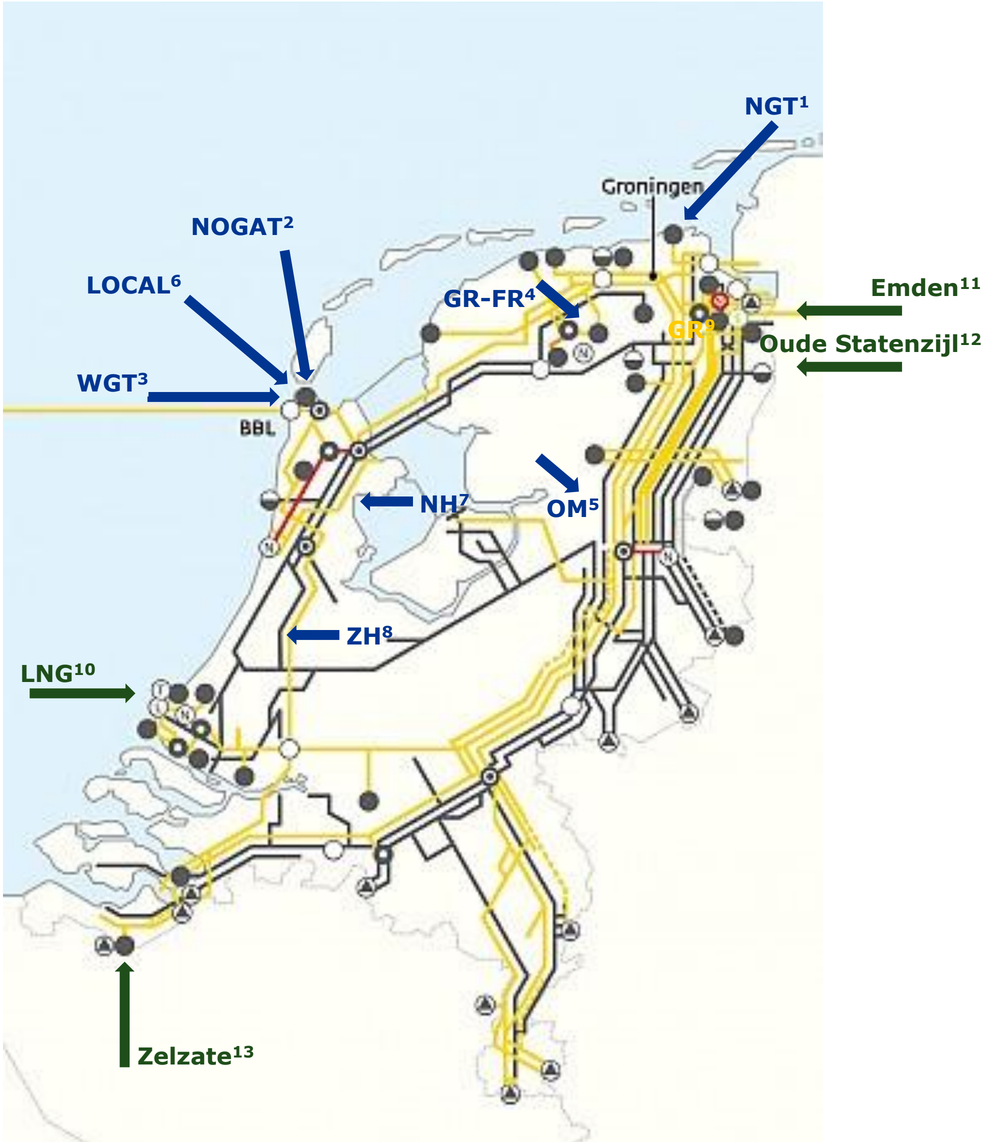

Figure 5: Schematic representation of the gas transmission network in the Netherlands
(source: Gasunie Transport Services, arrows indicating entry points inserted by DNV GL)

3.2 Gas quality development

As mentioned above, the H-gas transmission network is supplied with gas from various sources, on- and offshore from the small gas and import from Norway, Russia and as LNG. Below we show the expected gas quality development of gas from different supply sources based on information provided by GTS. We discuss the trend in small fields supply and import in separate sections. New developments such as shale gas and hydrogen-containing (bio)gases are not considered in this analysis.

3.2.1 Small fields supply

Gas supplied from the small fields is diverse in terms of gas quality. For each individual gas field the gas quality is uniform, but in many cases gas from more fields is combined in one entry point of the network of GTS. Therefore the gas quality at the entry point can be diverse.

The cumulative capacity profile of all the small gas fields is shown in Figure 6 and Figure 7. The graphs show the 2014 forecast of the capacity per Wobbe Index band. The capacity is in so-called tel quel (t.q.) which is the volumetric amount of gas in the system at that specific gas quality under normal conditions (temperature = 0 degree Celsius and pressure = 1 bar). In the data provided, a distinction is made between capacities including and excluding so-called futures. The futures represent those new capacities which might be found and explored, but which are not proven yet. The specified values of the future capacities are uncertain. First of all, the gas quality of the future capacities are arbitrarily assumed to be equal to the gas quality of the existing gas fields close by which are already in production. Moreover, the capacity of the futures strongly depends on the technical and economic feasibility of the development of the gas fields. And finally, there is always the possibility that gas fields are found with presently unknown gas qualities. The resulting Wobbe index at the entry point of the Gasunie network is assumed to be the capacity weighted Wobbe Index.

From Figure 6 and Figure 7 it becomes clear that the total production of the small fields is in decline. By 2032 the total capacity is expected to be almost three times lower than the 2014 capacities. When the futures are not taken into account, the total capacity will be 15 times lower compared to 2014 (see Figure 7).

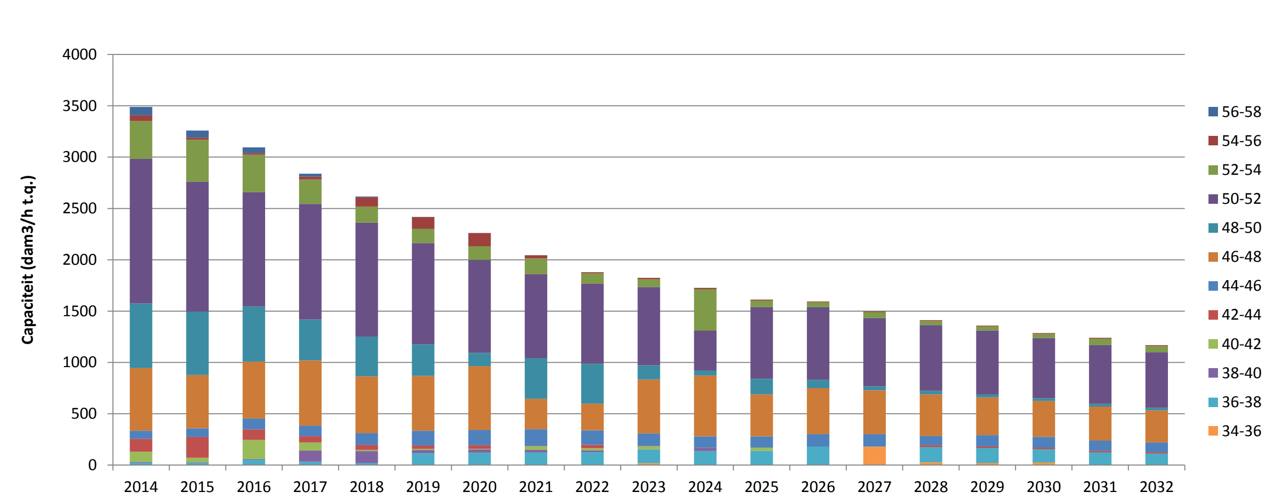

Figure 6: Capacity per Wobbe Index band of the 2014 forecast for all small fields combined – including futures
(source: Gasunie Transport Services)

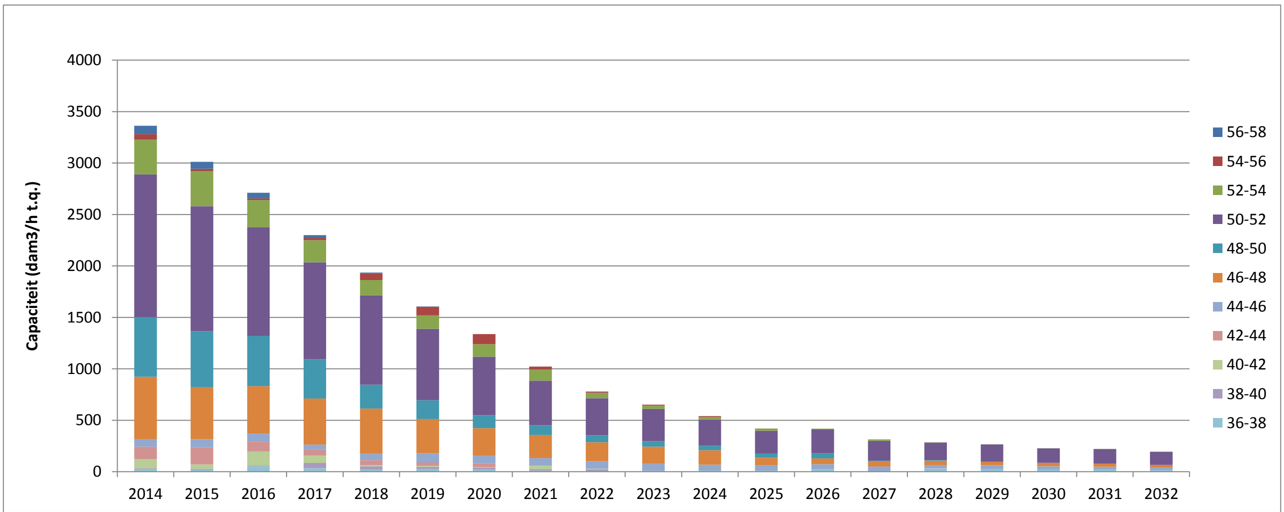

Figure 7: Capacity per Wobbe Index band of the 2014 forecast for all small fields combined - excluding futures
(source: Gasunie Transport Services)

In Figure 8 and Figure 9 the expected development of the gas quality from each small field supply is plotted excluding and including futures, respectively. Next to that the existing Wobbe Index bandwidth for H-gas and G-gas at exit points in the network is indicated as a reference as well. The Wobbe Index bandwidth currently in place for exit points in the gas transmission network for H-gas is 47–55.7 MJ/m^3.

One might note that the range of Wobbe Index in Figure 8 and Figure 9 is slightly different compared to the bar charts in the figures above. This is due to the fact the data in Figure 6 and Figure 7 shows the data for the individual fields whereas the figure below shows the resulting gas quality for each supply route (i.e. region/province).

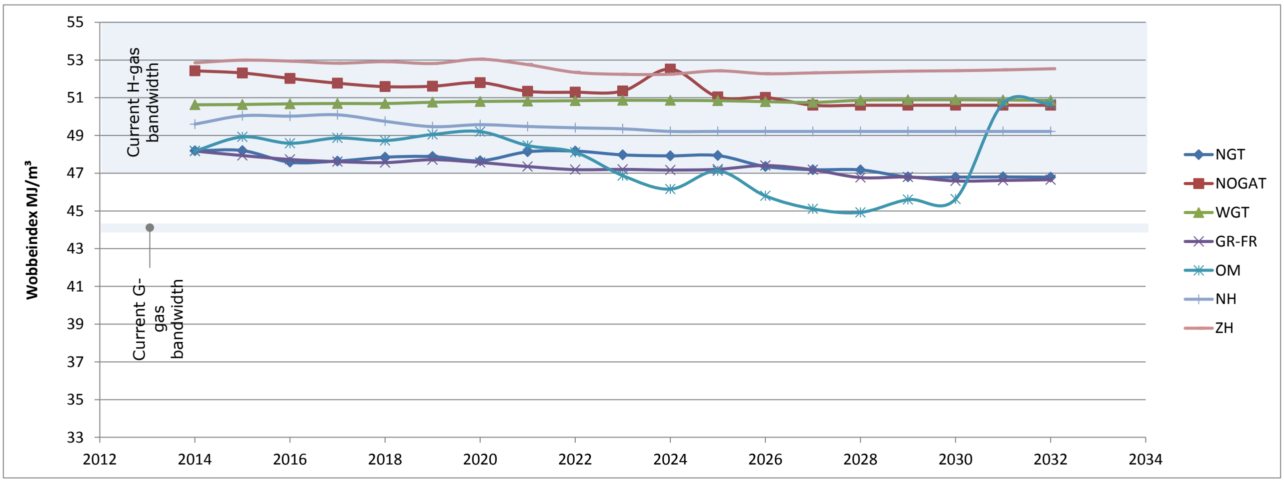

Figure 8: Expected Wobbe Index of the small fields excluding futures

(source: Gasunie Transport Services)

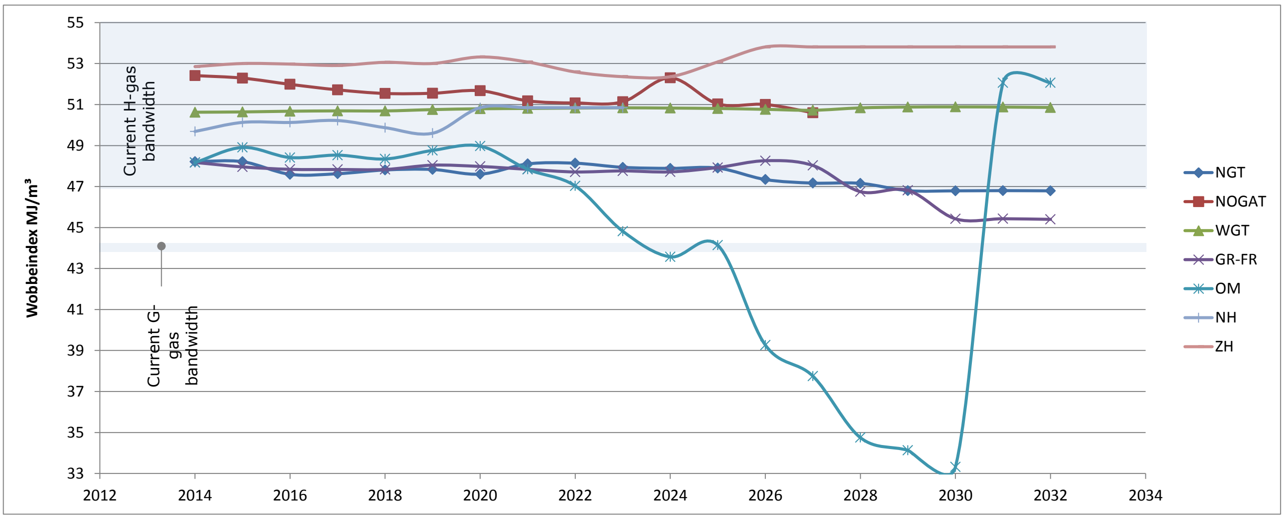

Figure 9: Expected Wobbe Index of the small fields including futures
(source: Gasunie Transport Services)

From the figures above it becomes clear that the forecast of the Wobbe Index bandwidth of gas produced from the small fields becomes wider in future.

3.2.2 Import

Next to indigenous production, gas is also imported. The main import flows enter the gas transmission network via de entry points Emden and Oude Statenzijl and via the entry point at the GATE LNG terminal.

Gasunie Transport Services assessed the quality of the gas imported in the Netherlands. GTS states explicitly that it should be noted that factual information regarding the future composition of gas is very limited (basically no information on Russian imports). The expectation is that the imported gas will have the quality as specified in the table below.

Table 3-2 Wobbe Index of gas imported in the Netherlands (MJ/m^3)[3]

Import	Lower limit	Average	Upper limit	Bandwidth
Emden (import from Norway)	51	53	54	3
GATE terminal (LNG import)	53	55	55.7	2.7
Oude Statenzijl (import from Russia)	51	53	55	4

For Norwegian gas imported via Emden, the expected Wobbe Index bandwidth is based on the measured gas quality of historic gas flows. The minimum measured Wobbe Index is 51 MJ/m^3, the maximum measured Wobbe Index is 54 MJ/m^3. Given the 'Ministeriële Regeling' of the 1st of October 2014 the Wobbe Index is allowed to be as high as 55.7 MJ/m^3, but this is not expected since in Norway the higher hydrocarbons are extracted from the gas and sold separately. We remark that changes in the hydrocarbon market can affect the commercial value of the extracted hydrocarbons and thus maximum value of the Wobbe Index.

The Netherlands can be supplied in the form of LNG at GATE terminal. Basically, LNG from any source can arrive at GATE. The composition of LNG from various sources worldwide varies substantially. As can be seen in the report from the association of LNG importers (GIIGNL)[4], the average Wobbe Index of LNG (taken at 25/0) varies from 56.77 MJ/m^3 from Libya to 53.51 MJ/m^3, which is nearly pure methane from Alaska. For the expected range for GATE, we observe that the maximum Wobbe Index is effectively limited by the Ministerial limitation of 55.7 MJ/m^3, while the lower limit for imported (or bio) LNG is given de facto by the Wobbe Index of methane with traces of nitrogen, roughly 53 MJ/m^3.

Gas entering the system at Oude Statenzijl will mostly be gas from Norway and partly gas from Russia and Germany. The expectation is that gas supplied to Europe in the next 10 years will largely be from the same existing source (Yamal field). This gas is high in methane content. Operational information exchange between Gasunie Transport Services and Gazprom confirmed that it is not likely that the gas quality of those supplies will change. It is also not likely that gas from the Shtokman field in Russia will be transported by pipeline, but more likely via LNG (but also not expected in the next 15 years). The gas quality specification of Russian gas supplied via Nordstream at the entry point Greifswald in Germany is between Wobbe Index 51 MJ/m^3 and 55 MJ/m^3. The gas quality of the actual supplied gas volumes is stable at a level of 53.4 MJ/m^3. The specification of the lower limit of the gas quality bandwidth at Oude Statenzijl given in the table above is based on gas quality measurements of historic gas flows. The upper limit is set at the maximum Wobbe Index of gas supplied at Greifswald.

Summarizing it becomes clear that the bandwidth of imported H-gas is expected to be at most 4.7 MJ/m^3. This bandwidth is small compared to the gas quality bandwidth of the small field gases as presented in the previous section. In the long term when the small fields are fully depleted and the market will be solely supplied with imported H-gas, the bandwidth can thus be set this narrow. A wider bandwidth is only required if other supply sources, such as the small fields, require so. This is a long term transition situation.

3.3 Projection of demand and supply

From the previous section it becomes clear that the gas produced from the small gas fields has a rather broad gas quality bandwidth whereas imported H-gas has a more narrow gas quality bandwidth. The gas transmission network has to accommodate gas from both sources. The information provided in the previous section was specified in terms of capacity. In order to get insight in the share of supply from

[3] Here we note that the maximum of 55.7 MJ/m^3 has been determined by the Dutch government.
[4] GIIGNL, "The LNG Industry", 2014, p. 12. http://www.giignl.org/

small gas fields and supply from imported H-gas, the volumes supplied from these different sources is shown in the figure below.

Figure 10: Demand and supply projection
(from Network Development Plan 2015 of Gasunie Transport Services, kWh/year converted to bcm/year by DNV GL)

The Dutch supply shown in the figure above is taken from the Network Development Plan 2015 [29]. The data on Dutch supply includes gas from both the Groningen gas field (G-gas) and the small gas fields.

It should be noted that the policy for the production from the Groningen is currently a subject of political debate. The final outcome of this debate is not known yet; therefore this analysis is based on the most recent information from information the Network Development Plan. This trend might change in future. The data on Dutch supply comprises the small fields supply including futures. As mentioned before, it should be noted that these values are uncertain. The capacities and volumes of proven reserves which will actually be produced in future will strongly depend on the technical and economic feasibility of the development of these fields.

The yearly demand projection is also taken from the Network Development Plan. Three demand scenarios are considered in that document, namely 'Green focus', 'Cooperative Growth' and 'Limited Progress'. For the remainder of this analysis we have (arbitrarily) chosen the Cooperative Growth scenario demand level. It should be noted that demand (black line with label NL Demand) excludes L-gas exports but includes the industrial demand for domestic H-gas.

As stated in the Network Development Plan, 'the production surplus that has characterised the Netherlands for so many years will no longer be in place by around 2025; the precise year will depend on the demand profiles in the three scenarios and the production profile …. From then on, the Netherlands will be a net gas importer.' The Netherlands will thus require additional gas supplies. This will have to be provided by additional H-gas imports. Therefore, in the long run significant capacities and volumes of H-gas with a Wobbe Index between 51 MJ/m^3 and 55.7 MJ/m^3 are expected to be imported. In the figure above the line with label 'New H-gas import' indicates the additional H-gas volumes which will have to be imported in order to match overall supply and demand.

In the next two sections we assess the implications of the H-gas quality bandwidths and the gas quality management options which can be used to manage and combine the different gas quality flows in the future.

3.4 Implications and limitations of maintaining H-gas quality bandwidths

In the previous sections we described the expected development of gas quality, capacity and volume for small field gases and the H-gas imports. As a summary the total capacities from the small gas fields is aggregated in Wobbe index bands of 1 MJ/m^3 in the figure below. We use this information as a starting point for determining which capacities can and cannot be directly accommodated for a certain H-gas quality bandwidth.

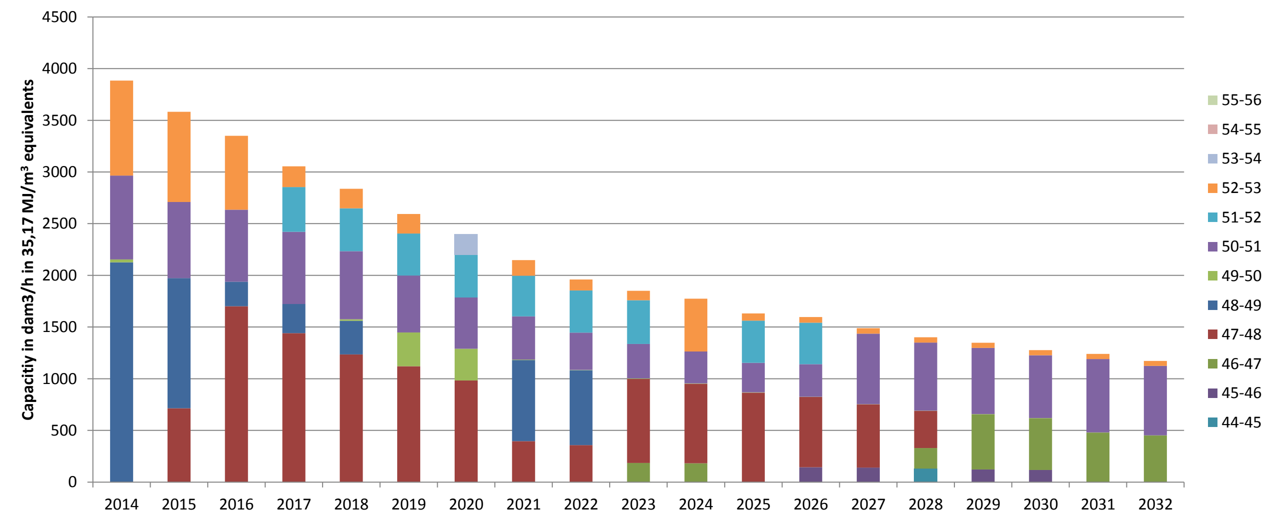

Figure 11: Capacity distribution of small field gas per Wobbe Index band (including futures)

The task at hand in this study is to arrive at a recommendation for the future gas quality bandwidth in the system. We assess the three cases with different gas quality bandwidths. In the next section we specify these three cases.

3.4.1 Three cases with different gas quality bandwidths

We defined three cases to get insights in the implications for and limitations of gas quality management options when selecting different Wobbe. These cases are:

- Case 1: A narrow Wobbe bandwidth of 2 MJ/m^3 as currently existing in Germany. We set this bandwidth at Wobbe Index 51-53 MJ/m^3. The lower limit of 51 MJ/m^3 is chosen since this is the expected lower limit of H-gas imports.
- Case 2: A wide Wobbe band of 8 MJ/m^3 similar to the existing bandwidth for supplying H-gas at an exit point and to the EASEE-gas range. For illustrative purposes, we set the bandwidth at Wobbe Index 49-57 MJ/m^3, where 57 MJ/m^3 is close to the maximum Wobbe Index of commercially traded natural gases.
- Case 3: A distribution band corresponding roughly to the distribution ranges for the UK, France, Denmark and Belgium, 4.7 MJ/m^3. We set this bandwidth at the level of 51-55.7 MJ/m^3.

With maintaining a given H-gas Wobbe Index bandwidth, parts of capacity produced from the small gas fields and/or the imported H-gas will be outside the gas quality envelope. The gas with a Wobbe Index outside a chosen bandwidth will be referred to as 'off spec gas'. These volumes cannot freely be injected and transmitted in the gas transmission network. Ways have to be found how to deal with these capacities and volumes of gas.

In the next two sections we assess the need for two the gas quality management options blending and ballasting with nitrogen.

3.4.2 Blending

Blending is a gas quality management option where gas with a Wobbe Index below the defined Wobbe Index bandwidth is blended in a gas flow with a higher gas quality to such an extent that the resulting gas flow is above the lower range of the Wobbe Index bandwidth. In practise this means that the remaining supply from the small gas fields needs to be accommodated by blending into the H-gas import flows. Of course, blending with low Wobbe gas also lowers the Wobbe Index of the high Wobbe gas with which it is mixed.

We explain the calculation of the required blending capacity for Case 1 with the Wobbe Index bandwidth of 2 MJ/m3 @ 51-53 MJ/m3. The other graphs and tables show the results for the other two cases as well.

As an illustration we show the implications of setting the Wobbe Index bandwidth at 51-53 MJ/m^3. The figure below shows which capacity shares of are inside (green bars) and outside (blue and red bars) of this gas quality envelope.

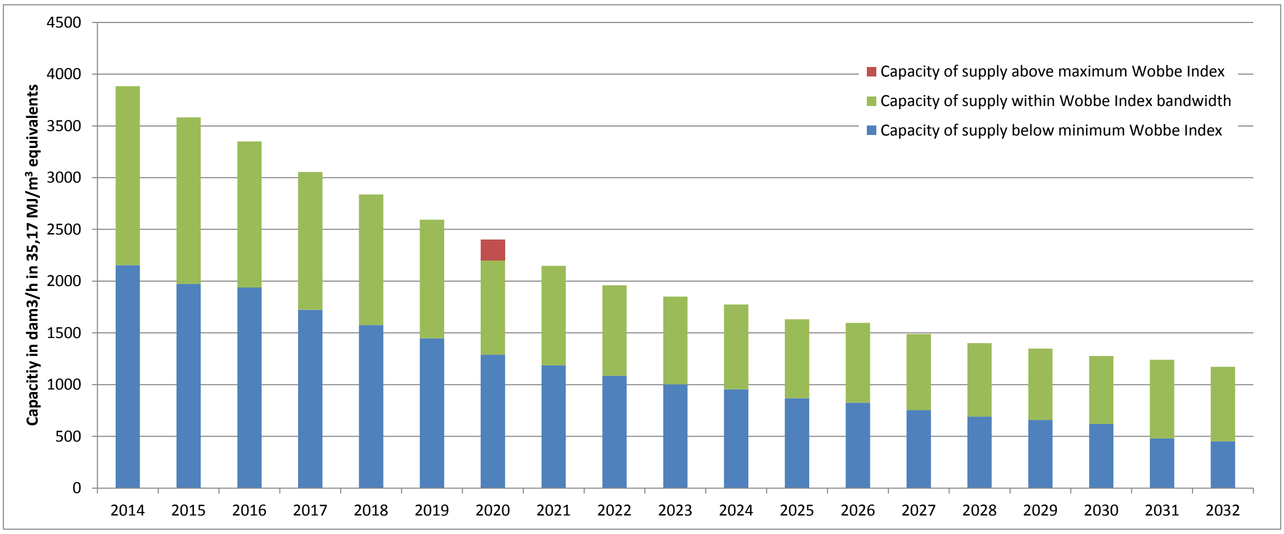

Figure 12: Small field capacities inside and outside the Wobbe Index band of 51-53 MJ/m^3 for case 1 (including futures)

The figure above shows the capacity which is outside the Wobbe Index bandwidth of case 1. In order to assess the implications for gas blending requirements we also need insight in the annual volumes. To make the translation to annual volumes we assume a total of 6720 operating hours per year. This corresponds to an availability of 77%. All volumes from the small fields are converted into 35.17 MJ/m^3 equivalent volumes. In the figure below we show the annual volumes of gas from small fields with a quality below the lower limit of the Wobbe Index bandwidth. We show the volumes for all three cases defined above.

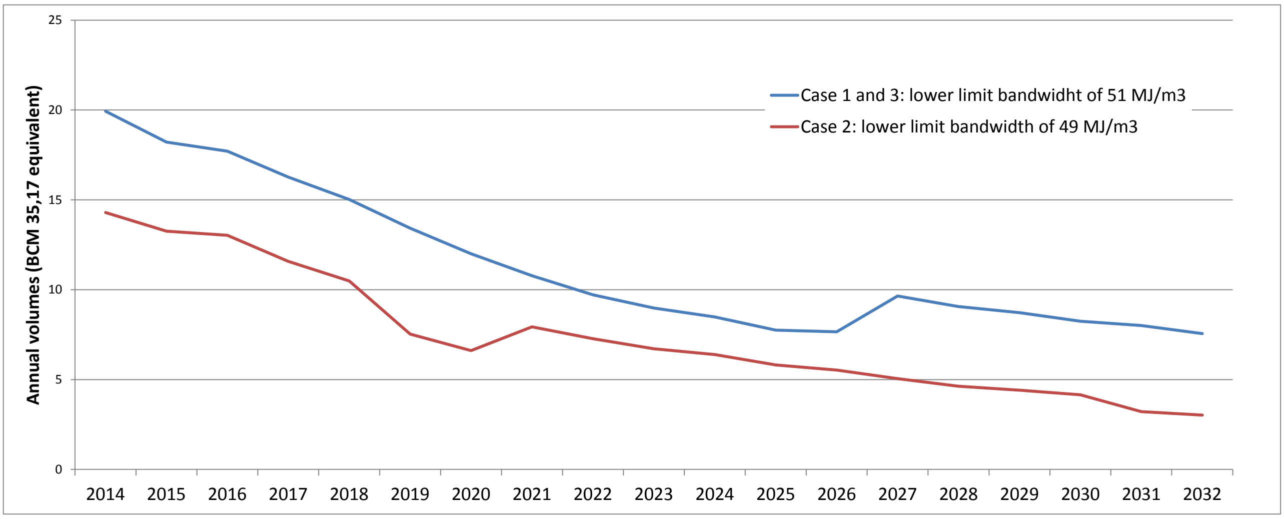

Figure 13: Small field annual volumes with a quality below the lower limit of the Wobbe Index bandwidth in the three cases (including futures)

From the figure above it becomes clear that when the lower limit is higher a larger annual volume of gas falls outside the gas quality bandwidth. These volumes will have to be blended into either the richer H-gas flows or into the G-gas flows. The latter bandwidth is relatively small, but may have substantial accommodation space due to large volumes, especially in the earlier years.

In the remainder of this section we focus on blending gas from the small fields in richer H-gas import flows. Gas from the small fields with a Wobbe Index below the lower limit of the bandwidth can be blended in richer H-gas import gas flows to the extent that the Wobbe Index of the combined flow is above the minimum Wobbe Index. In order to gain insight in the required H-gas flows, we have assumed that the average Wobbe Index of the H-gas import flows is 53 MJ/m3. For each portion of off-spec gas we have estimated the volume of H-gas required bringing the combined flow to a minimum Wobbe-Index of the bandwidth. The results are shown in the figure below for each Wobbe Index bandwidth. When the lower limit is higher a larger annual volume of gas falls outside the gas quality bandwidth. In this figure the volumes of H-gas that will be imported in future are shown as well. These are the additional H-gas imports required to satisfy overall demand (see Figure 14 – New H-gas imports).

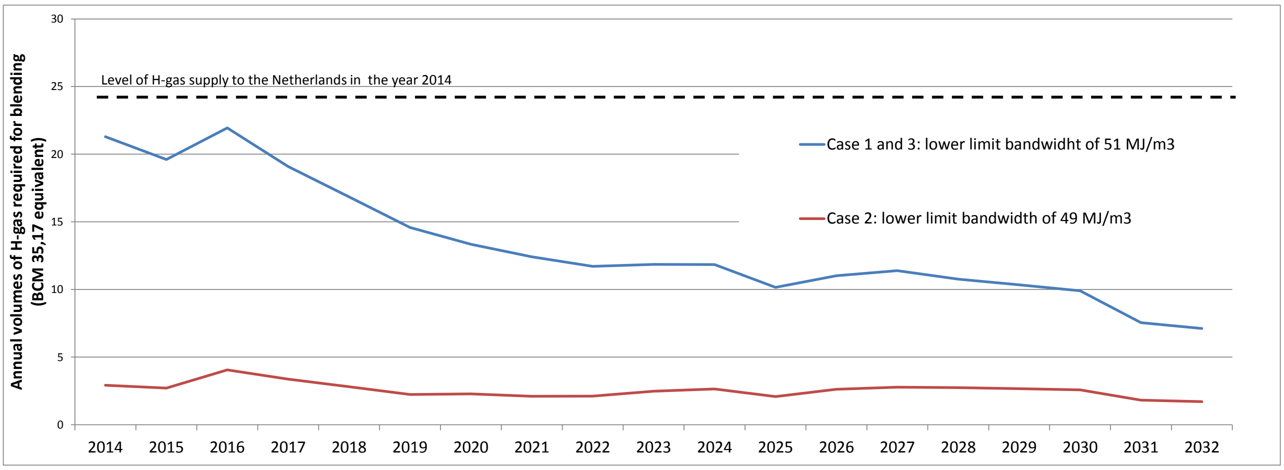

Figure 14: H-gas volumes required for blending off-spec small field supply in the three cases (including futures)

Setting the lower limit of the bandwidth at a higher level will cause a larger volume of small field gas being off-spec and thus requiring a larger volume of H-gas into which this off-spec can be blended into. Setting the lower limit of the bandwidth at a lower level (49 MJ/m^3) has two advantages in terms of gas quality management. First of all the volume of off-spec gas is lower (see the red line in the figure above) and also larger volumes off-spec gas can be blended in the other streams because the on-spec volumes are higher and the Wobbe Index of the resulting flow can be lower.

In this figure we indicate the level of H-gas supply to the Netherlands in the year 2014 as well. In that year a volume of 24 bcm was supplied to the Netherlands at the entry points Emden, Oude Statenzijl and GATE. In 2013 this volume was 23 bcm. From this figure it can be concluded that sufficient H-gas is available today already to accommodate the off-spec gas in the three cases. In future the volume of H-gas supply will only become larger since from 2025 onwards the Netherlands will become a net importer of gas (see Figure 10 – New H-gas import). We would like to stress that this is just an order of magnitude indication, based on the assumption that the imported H-gas always has an average Wobbe of 53 MJ/m^3. This cannot always be guaranteed, it depends on which gas flows shippers bring into the system. Furthermore this high level approach considers the system as a whole; it does not consider potential infrastructure limitations within the system (having the blending stations and H-gas flows with the right capacity at the right place). Such an analysis would require detailed network simulations.

However, blending stations are in place already to accommodate the supply from the small fields' flows at various places in the network. As such the available blending capacity should thus be sufficient to accommodate the supply from the small fields. The question is if the existing blending stations are located at the right place in the network in future as well. This assessment would require detailed hydraulic network simulations; this is outside the scope of the analysis.

A similar analysis could be made for blending off-spec small field gas in the G-gas network. The Wobbe Index bandwidth in the G-gas network is much smaller, but especially in the short to medium term when the volumes are considerably larger than the H-gas volumes it provides substantial accommodation space for blending off-spec gas. Once the G-gas supply goes further into decline also the blending capacity in the G-gas network becomes small.

3.4.3 Ballasting with nitrogen

The other gas quality management measure considered here is ballasting with nitrogen. Gas supply with a Wobbe Index which is higher than the upper limit of the gas quality bandwidth can ballasted with nitrogen in order to lower the Wobbe Index of the resulting mixture.

As explained in section 3.2.2, the expectation is that the H-gas which will be imported in the Netherlands will have a Wobbe Index between 51 and 55.7 MJ/m^3.

The option of nitrogen ballasting is relevant for case 1, where the upper Wobbe Index limit is set below the maximum of the international range of natural gases (around 57, as in the maximum of case 2) and below the expected maximum import Wobbe Index of 55.7 MJ/m^3. Clearly, since the maximum of case 2 is already at this limit, no nitrogen ballasting is required.

In this section we estimate the required nitrogen volumes and associated costs on an annual basis. In order to do so we have made a number of worst case assumptions regarding future gas supply sources and the Wobbe Index of these supply sources:

- We assume that the maximum capacity of GATE LNG terminal is used. The maximum annual throughput is 12 bcm.
- Furthermore we assume that gas from Russia and Norway each have an equal share in supply. Assuming a total gas demand in the Netherlands of 42.5 bcm, and assuming that ultimately all consumers are supplied solely with H-gas, the required supply from Russia and Norway is 15 bcm each.
- The expected minimum Wobbe Index of gas at GATE terminal is 53 MJ/m3. This means that all gas from GATE will have to be ballasted with nitrogen in order to lower the gas quality. A worst case assumption is that gas will always be supplied at the maximum expected Wobbe Index of 55.7. This means that all the volumes supplied via GATE terminal will have to be ballasted with nitrogen to reach a Wobbe Index of 53 MJ/m^3.

Using these assumptions DNV GL estimates that at maximum an annual volume of 0.45 bcm nitrogen is required at GATE terminal in order to ensure that the upper gas quality limit of this import flow can always be reduced to 53 MJ/m^3. If also gas from Russia and Norway is supplied with the maximum expected Wobbe Index (Wobbe Index of 55 MJ/m^3 and 54 MJ/m^3 respectively), this will require another annual volume of 1.1 bcm nitrogen.

To determine the associated annual costs we combine the annual volume of nitrogen with a cost level of producing nitrogen. For the calculations we used the cost levels for nitrogen production of Gasunie Transport Services. These costs levels are also recognized by the regulatory authorities and the Dutch government. The OPEX of a nitrogen plant the size of the existing large scale nitrogen production plant at the Ommen station is 3.3 €ct/m^3 N_2. Also the investment costs of a nitrogen plant have to be reflected in the price of nitrogen. The CAPEX of such a station is €1200 per m^3/h N_2 installed. In order to determine the CAPEX element in the commodity price of nitrogen we made a number of assumptions. We base the calculation on a large nitrogen plant (similar to the size of the plant currently in the station 'Ommen'). The regulatory asset life of such a facility is set at 30 years and we assume a load factor of 0.28. Combining these assumptions results in a CAPEX element in the price of 1,6 €ct/m^3 N_2. Combining the OPEX and CAPEX elements results in a price for nitrogen of 4.9 €ct/m^3 N_2. The costs of producing the earlier mentioned 1.1 bcm nitrogen thus amount 52 million euro annually. We also note that the cryogenic nitrogen production is energy intensive, resulting in a substantial carbon footprint of such a plant. In this scenario, nitrogen ballasting will have to be done perpetually and will result in annually recurring costs.

Gas quality conversion using nitrogen ballasting is already used today in the gas transmission network, among other things to reduce the Wobbe Index of gas coming from the Gate terminal. It should be noted that the installed capacity of nitrogen production plants and associated blending stations in place today is higher than the volumes required in future. Although the facilities are in place, the annual costs of nitrogen production still have to be accounted for when nitrogen is produced in these facilities.

In this assessment we do not consider costs for modifying appliances. The assumption is that the existing appliances will be replaced naturally over time and that the new appliance can handle the Wobbe Index bandwidth. In that arrangement, no additional costs due to the choice of bandwidth are incurred.

3.4.4 Alternative gas quality management options

In the previous section we discussed and evaluated the use of two conventional gas quality management options. These options are successfully used in the network of GTS for decades already. Next to the conventional options of blending small field gas in richer H-gas flows and ballasting with nitrogen, also more non-conventional approaches towards dealing with off-spec gas supplies are identified. The following options are identified:

1. Ballasting H-gas with air at gas delivery station at the interface between the gas transmission network and the gas distribution network.
2. Isolating off-spec gas in a separate part of the gas transmission network and supplying to a dedicated group of consumers.
3. In-situ production of electricity from off-spec gas.
4. In-situ production of LNG.
5. (Temporary) access restriction for off-spec gas.

A description of these options is provided in Appendix C. For each option we briefly describe the approach and we discuss advantage and disadvantages of these approaches in a qualitative fashion. A detailed assessment of these alternative options is not relevant for evaluating and advising the long term H-gas quality bandwidth. The selection of the most suitable options (or combination of options) can be made over the course of time, shortly before the transition to the new gas quality bandwidth starts. The uncertainties in terms of capacities, volumes and gas quality of the gas entering the system will also be much lower at that point in time.

We note that the potential measures that support the intake of gas with a Wobbe Index lower than the minimum Wobbe Index of H-gas imports are expected to be temporary. The volume of gas from the small fields is expected to become very small after 2030. These options might however be considered in the transition period. The use of the (non-conventional) gas quality management options described here is at present also seen more as transition measures and rather than permanent. They too might be useful during the transition period.

3.5 Summary of observations

In this chapter we assessed the expected gas quality bandwidth of gas that will be produced and imported in the Netherlands in the future. In summary we have the following observations:

- The forecast of the Wobbe Index indicates that the gas quality range of gas produced from the small fields is broad, currently 35-56 MJ/m^3 and the forecast indicates that the bandwidth will become even wider in future. Supply from the small fields is however in decline. By 2032 the total capacity including futures is expected to be almost three times lower than the 2014 capacities. These futures are however highly uncertain. When the futures are not taken into account, the total capacity will be 15 times lower compared to 2014. In 2032 supply from the small fields will then only be 3% of demand (20% if the futures fully materialize).
- In the future, more and more gas will be imported via pipeline from Norway and Russia and in the form of LNG worldwide. From around 2025 onwards the Netherlands will become a net importer. Compared gas produced indigenously from the small fields, the gas quality bandwidth of imported H-gas is much narrower. The Wobbe Index of H-gas imports to be admitted to the H-gas network are expected to be in the range of 51-55.7 MJ/m^3.
- Three cases with different Wobbe Index bandwidths were evaluated. Particularly the case with a narrow bandwidth of Wobbe Index 51-53 MJ/m^3 requires the most gas quality management measures in the gas transmission network.
  - On the one hand gas blending capacity is required to blend the remaining off-spec small field gas in H-gas flows. Estimates indicate that after the year 2028 sufficient new H-gas import flows are available to absorb the off-spec small field gases.
  - Setting the upper limit of the Wobbe Index bandwidth substantially below the maximum expected Wobbe Index of H-gas imports will required potentially large capacities of nitrogen ballasting. In a worst case estimate these costs might amount to 52 million euro annually. This blending of nitrogen will then be needed permanently.
- We note that the potential measures that support the intake of gas with a Wobbe Index lower than the minimum Wobbe Index of H-gas imports are expected to be temporary. The volume of gas from the small fields is expected to become very small after 2030. The use of the gas quality management options described here is at present seen more as transition measures and not as permanent.

4 INNOVATION

Clearly, appliance innovation offers a dedicated route towards maximizing fuel flexibility. An inventory has been made to determine the existing products and the development of innovative products aimed at extending the fuel flexibility of domestic end-use equipment, e.g. active control systems. The inventory is based on interviews with different stakeholders and collecting existing information available, including progress made in existing innovation programs such as SBIR. To assess the impact of the innovations we focus on the reliability of the system, additional costs and time-to-market.

4.1 Gas quality control systems for premixed appliances

4.1.1 Development of innovative active control systems

The development of active control of appliance performance with varying gas composition has been a subject for decades. Recently, DNV GL developed a proof-of-principle of a feed forward control system to guarantee safe and optimal performance for a broad range of gases (L + H Wobbe band) and large Wobbe fluctuations. The control system was implemented in a domestic boiler and showed excellent performance over the entire L- and H gas Wobbe band and could handle large fractions of hydrogen in natural gas as well. However, the sensors needed to measure the gas composition are currently far too expensive for domestic appliances. For example, a Swiss company (MEMS) will introduce a gas composition microsensor in the market at the beginning of 2016 for a price of about 200-1.000 euro, which is an order of magnitude too expensive for domestic application. Substantial research effort is being made, e.g. ref. [26] and progress is being reported, e.g. Ref. [27] regarding the development of (cheap) micro gas-composition sensors, but the hurdles encountered are expected to challenge the commercial introduction of sensors for the next 10 years.

Currently, within the Dutch innovation program SBIR two programs are conducted to develop an active control system for domestic premixed boilers. In one of the programs called “gasadaptief modulerend regelsysteem” a burner control system is developed that optimizes the combustion by changing the fuel-to-air ratio by measuring the ionization current in the flame. The active control system will not replace the pneumatic control system of premixed boilers but will be used as an add-in that fine tunes the fuel-to-air ratio to obtain optimal combustion. The advantage of the control system is that it can be easily integrated (retrofit) into premixed domestic boilers having the traditional pneumatic fuel-to-air ratio control system and it fulfills the safety requirements according to the GAD. The additional costs for new appliances that will be equipped with the active burners control system are low and the results are promising. Alternatively the control system can be implemented as retrofit in case the appliance is prepared for this. This means that the appliance should include all necessary approved electronics needed to control fuel-to-air ratio based on the measured ionization current, the hardware will be built-in in a later stage.

The active control system will allow the boiler to handle a large range of gases (L- and H-Wobbe band) including e.g. 10% hydrogen. The active control system has already been tested successfully and the manufacturer indicates that the time to market is expected to be about one year from now. We note however that field tests have not yet been performed and approval is not yet in place. The time to market could therefore be longer. Cooperation with manufacturer(s) is needed to integrate the novel control system into domestic premixed boilers. The estimated time-to-market of a complete domestic boiler system is about 1 year for existing appliances and about three years for a complete new appliance according to the manufacturer of the control system.

The company currently works on the development of a similar system for the so-called "light commercial" market, up to 150 kW. Furthermore a second control system by using an oxygen sensor is in development for industrial applications up to 3MW.

Recently, a Dutch appliance manufacturer developed a domestic boiler with active control Ref. [30] that can handle a broad range of gas qualities; 100% biogas, propane and natural gases. This appliance is equipped with an active fuel-air control which allows optimal combustion based on temperature measurement, Ref. [30]. The time-to-market is expected to be less than one year and the cost of the boiler is expected to be about 1.200-1.400 Euro.

4.1.2 Commercially available appliances having active control system

Several manufacturers e.g. Weishaubt and Viessmann have already introduced domestic E-band (premixed) boilers on the market with an active fuel-air ratio control based on flame ionization. According to the manufacturers these appliances can handle a broad range of gas qualities (E-band) and able to handle rapid changes in gas quality. The appliances are sold mainly in Germany for about 1.700, 00 Euro. It is to our knowledge unknown how these appliances respond to hydrogen in natural gas.

DNV GL has investigated the performance of the Viessmann Vitodens with an active fuel-air ratio control based on flame ionization. In tests the effects of variations in Wobbe Index on performance at both stationary and by rapid fluctuations is studied. During the experiments the boiler was allowed to warm up using Groningen gas (44.3 MJ/m^3), whereupon the gases were switched to "LNG" between 48.3 MJ/m^3 and 57.7 MJ/m^3 (using methane/propane/nitrogen mixtures), the results show only a marginal increase in CO emissions, indicating the adequacy of the control system. Analysis of the results, including the actual control of the air factor shows that the air factor varies, albeit slightly, with gas composition, yielding the result that G-gas has slightly higher CO emissions than the gas at 48.3 MJ/m^3. This is to be expected, since the ionization signal is not directly related to the air ratio; but it is certainly good enough for the purposes for which it was designed. Dynamic experiments, by switching between 48.3 and 57.7 MJ/m^3 on the same time scale as described above, showed a maximum overshoot of 3 ppm, on an average level of ~40 ppm at low thermal load, lasting roughly 30 seconds was observed. This is not deemed a cause for concern.

4.1.3 Innovation for partially premixed appliances without a fan

Partially premixed appliances, for example cookers, ovens, and flow through hot water heaters contain bunsen type of burners. In these types of appliances the gaseous fuel is injected into a Venturi and the entrained air is mixed with the fuel before entering the burner. Variation of the gas quality has a direct impact on the performance of these types of burners.

A large burner manufacturer is currently developing a new generation of gas burners that fulfils the need for both high performance and capacity to deal with flexible gas quality. One of their research topics is part of the SBIR project 'variabele gassamenstelling' and aims at the development of a gas detection-system on a gas hob. The idea is that the gas flow to the burner is influenced based on the information of the gas detection system. In this way a safe working of the burner would be possible for a wider range of gases. The research focuses on development of a gas hob that can burn safely over the entire L- and H gas Wobbe band. One of the consequences of the use of sensors is the introduction of electronic control. Of course this will have an impact on the price. However, price is not the only driver for a successful market introduction. Other factors are the technological feasibility, and of course the process of the government on the actual introduction of a variable gas quality. If the market demand a flexible Wobbe band (L-gas + H-gas) than the time-to-market of a sensor based appliance is about 5 years. The current estimation is that the extra costs for a sensor based hob burner system ranges from 300-700 euro.

Besides the above mentioned innovation regarding hob burners to our knowledge no products and/or innovation programs aimed at extending the fuel flexibility for partially premixed domestic appliances such as flow-through hot water heaters exists. Since the application of pre-mixed appliances is large it is strongly recommended to promote the development of partially premixed appliances that are suited for a broad range of gas composition.

4.1.4 Innovation non-domestic burners

Large-scale burners in the commercial sector are mainly nozzle-mix burners (non-premixed). For these types of burners currently no control systems are commercially available to accommodate a wide range of gas compositions. However according to the opinion of DNV GL the development of a control system to allow a wide range of gas compositions is economically and technically feasible. Several control strategies are possible that can be integrated into an existing (safety) burner management system. Sensors to be used in combination with a feed-back control system are already available and economically affordable for burner systems with a load larger than 3MW. Additionally, gas composition sensors are needed for feed-forward control systems, the advantage of these control systems is that they can handle abrupt Wobbe fluctuations. It is expected that these sensors will be affordable in the near future Ref. [28].

At the time of writing, we are not aware of any manufacturer or supplier of large-scale commercial burner systems developing an integrated adaptive Feed-Forward control system that can accommodate a wide range of gas compositions and abrupt changes in gas composition or Wobbe Index.

4.2 Summary of observations

Summarizing the observations regarding the innovation of appliances:

- Several commercially available (premixed) appliances having active control systems are suited to operate at the entire E-band and to handle abrupt Wobbe fluctuations.
- Several promising developments of (inexpensive) control systems for premixed appliances are in progress to extend the fuel flexibility for both new domestic appliances and appliances already installed in the field that are appropriate for retrofit. Time to market estimated at roughly 1 year.
- Within the SBIR program a sensor based hob burner (cooker) is under development to guarantee high performance and capacity while using variable gas quality (L+H band).
- DNV GL is not aware of any existing developments or innovations to make other type of partially premixed domestic appliances, such as flow-through hot water heaters suited for a broad range of gas compositions.
- To allow a broad distribution band it is recommended to promote the development of fuel flexible partially premixed appliances.
- To our knowledge, no innovation regarding the development of fuel-adaptive control systems for non-domestic burners is currently being undertaken. However, several control strategies are possible and economically feasible.

5 SYNTHESIS

In this Chapter we combine the assessments described in detail above to advise the Dutch government in choosing a range of Wobbe Index for distribution that will provide the fewest restrictions in supply, while maintaining the safety and reliability of end-use equipment at the lowest (social) cost. To illustrate the advantages and disadvantages of the various choices regarding Wobbe ranges we defined three cases:

- Option 1: A narrow Wobbe bandwidth of 2 MJ/m^3, as currently existing in Germany
- Option 2: A wide Wobbe bandwidth of 8 MJ/m^3, matching the current stated bandwidth of Dutch H-gas quality.
- Option 3: A distribution band corresponding roughly to the distribution ranges for the UK, France, Denmark and Belgium, 4.7 MJ/m^3.

In the evaluation of these three cases the following points, discussed in the previous chapters, will be considered:

- The ranges of gases deemed to allow safe and reliable appliance performance, described in Chapter 2,
- The expected Wobbe range of future natural gases, described in Chapter 3. The advantages and costs of gas treatment, i.e., via nitrogen ballasting and blending, to match appliances and future gases are also considered,
- The progress in the development and costs of innovation in gas appliances aimed at extending the fuel flexibility of GAD end-use equipment, e.g. active control systems, described in Chapter 4.

Before discussing the three options we review the expected future distribution bandwidth and the assessment of the impact of the Wobbe Index bandwidth on H-/E-band appliances. All Wobbe Index numbers specified in this chapter are at (25/0).

5.1 Future supply and expected Wobbe bandwidth

In 3 we assessed the long term supply of natural gas in the Netherlands. Ultimately, when Dutch indigenous gas production becomes small, gas is expected to be supplied by pipeline imports from Norway and Russia, and as LNG from the worldwide market. The Netherlands is expected to become a net importer from 2025 onwards. The expectation is further that the imported gas will have a Wobbe Index between 51 and 55.7 MJ/m^3. The upper limit of 55.7 MJ/m^3 is set by the Dutch government.

This gas quality bandwidth is significantly smaller than the current standard bandwidth permitted in the H-network, from 47 to 55.7 MJ/m^3. The so-called small fields contribute predominantly to the lower half of this range. At the moment an annual volume of 25 bcm is produced from the small fields. Including unproven reserves (so-called futures) this volume will drop to 9 bcm in 2030. Depending on the technical and economic feasibility of the development of these gas fields, the capacity of the futures has a large degree of uncertainty. Excluding futures, the volume of the small fields decreases to 1 bcm in 2030.

Since common gas treatment for fermentation gas can readily produce methane with only modest residual CO_2 fractions, the Wobbe Index of future 'biomethane' is expected to also be within the range expected for imported natural gas. New developments such as shale gas and hydrogen-containing (bio)gases are not considered in this analysis.

5.2 Ranges of gases deemed to allow safe and reliable appliance performance

In Chapter 2 we assessed the existing experimental, theoretical and practical/experiential evidence regarding which bands of Wobbe Index maintain the safety and reliability of the population of H-/E-band appliances installed in the field. In our opinion, the distribution practices in the UK, France, Denmark and Belgium give the best reflection of a practical range for Wobbe Index: the years-long practice in these countries shows that appliance performance with distribution limits in the range 4-5 MJ/m^3 satisfies the national requirements and/or customs for safety and reliability in these countries. We also note that these countries have some form of active maintenance regime. Provided the adjustable appliances are properly adjusted, the laboratory experiments assessed in Chapter 2 support a range of 4-5 MJ/m^3, although these experiments require extra interpretation before being applied to the situation in practice. The theoretical analyses show that the approval regime does not safeguard the intended appliance performance in a number of situations. However, these analyses say nothing about the actual safe and reliable performance of appliances in the field. Therefore, we conclude that a bandwidth of in the range of 4-5 MJ/m^3 can be realized for appliances approved under the GAD[5].

5.3 Evaluation of options

5.3.1 Option 1: A narrow Wobbe bandwidth of 2 MJ/m^3

In Germany the local variation in Wobbe Index is generally limited to ± 1 MJ/m^3. As discussed in Chapter 2, this Wobbe bandwidth is much narrower that the 4-5 MJ/m^3 ranges experienced in the field in other countries.

Obviously, a narrow bandwidth requires either restricted access to the gas grid for new gases or gas quality management in the gas transmission/distribution network. The two conventional approaches, blending and nitrogen ballasting, can be used to achieve a narrow band. As discussed in Chapter 3, blending off-spec gas from the small fields with a gas with a higher Wobbe Index results in gas compositions within the Wobbe Index bandwidth provided the blending ratio is chosen properly. In Chapter 3, considering a lower Wobbe limit of 51 MJ/m^3, we estimate that an annual volume of 10 bcm of H-gas is required in the year 2030 to blend the remaining small fields gas supply. By 2030 sufficient H-gas should be available since an annual volume of 18 bcm imported H-gas is required to match supply and demand in the Netherlands. Therefore, in terms of available H-gas volumes for blending there are no limitations. Overall the capacity of existing blending stations is also sufficient to accommodate the supply from the small fields, although whether the existing blending facilities are located correctly is at present unclear.

Since the supply of low calorific small field gas is not sufficient to reduce the Wobbe Index of the supply of high calorific import gas to the upper limit of 53 MJ/m^3 considered in this case, nitrogen ballasting must be used. If we consider imported gases from Russia, Norway and as LNG, with expected upper Wobbe Index limits of 54, 55 and 55.7 MJ/m^3, respectively, potentially large volumes of nitrogen will be required. In a worst-case estimate, these costs can amount to 52 million euro annually. In addition, we note that the cryogen nitrogen production is energy intensive, resulting in a substantial carbon footprint of such a plant. In this scenario, nitrogen ballasting will have to be done perpetually and will result in annually recurring costs. In addition to cost, the necessity of continuous and perpetual ballasting (and

[5] As discussed in Chapter 2, potential issues of some equipment, such as that falling under EN 676, regarding maintaining emissions limits with a wide range of Wobbe Index are excluded from this discussion.

blending) burdens the gas infrastructure with a complex gas management system, particularly when considering the variability of the composition of the gas supply.

Recalling the arguments in earlier studies (such as in [2]), we observe that the 'transition route' upon which the Netherlands embarked, including this study, was intended to loosen the restrictions that a narrow band of gas composition places on the gas supply. And to bring the range of gas composition more in line with other European countries, such as Great Britain, France, Belgium and Denmark. Since the policy of the Dutch government is in essence a 'green fields' approach, in which choices regarding gas quality are made before the infrastructure is created, it does not seem logical at this juncture to choose deliberately for a narrow band, particularly when alternatives are within reach.

Regarding the developments in other EU countries, we note that according to our information Germany is starting its own 'transition', desiring to relax the restrictions on bandwidth imposed by the current state of the appliances. In the UK, there is also a desire to widen its (already relatively wide) bandwidth to higher Wobbe Indices, with an eye towards facilitating LNG import.

Regarding the introduction of renewable gases into the gas grid, the choice of a narrow band also limits and lowers the flexibility of the introduction of hydrogen and hydrogen-containing biogases to the natural gas grid.

5.3.2 Option 2: A wide Wobbe band of 8 MJ/m^3

A wide Wobbe range of, for example 49-57 MJ/m^3, means that all small field gases can easily be accommodated into the natural gas grid, either directly or through blending, and no nitrogen ballasting is needed for LNG coming into the system. Furthermore, having a wide Wobbe band allows a more flexible accommodation of sustainable gases, such as hydrogen and biogas (at least in terms of Wobbe Index, see below) and thus will promote introduction of sustainable gases into the natural gas grid. From this we conclude that a wide Wobbe range gives the grid operator more flexibly to deal with the different gas compositions that can be expected in the future.

However, only a small part of the appliances currently commercially available can accept a Wobbe band wider than 4-5 MJ/m^3 while maintaining safety and reliability. This implies that substantial effort must be made to develop new appliances that can offer the guaranteed performance. There are already lean-premixed appliances, such as domestic boilers, having active control that can accept a wide range of gases easily, and the price of such appliances is commercially reasonable. With the exception of hob burners, to our knowledge no innovation regarding the development of fuel-adaptive active control systems to widen the range of gases for partially premixed domestic burners and non-domestic burners is currently being undertaken. While for non-domestic burners several control strategies are possible and economically feasible, no large potential is currently foreseen for partially premixed domestic burners, such as in hot water heaters, local heaters, etc., since innovation is challenging and, in our opinion, at present not economically attractive. This further implies that choosing a wide Wobbe band can result in a large shift in the use of gas for the end user: without a large-scale innovation effort to develop functional and inexpensive partially premixed appliances, these types of appliance would then disappear from the market. In the context of the future Wobbe range discussed above, the enormous investment in appliance development seems both unrealistic, due to the long lead time for development, and unnecessary, given the dwindling supply of small field gases.

5.3.3 Option 3: A distribution band of 4.7 MJ/m^3

The distribution bandwidth of 4-5 MJ/m^3 observed in other countries matches very well with the expected import band of future H-gases of 51-55.7 MJ/m^3, suggesting that this range may provide a reasonably future-proof choice, and an optimum between appliance performance and expected gas supplies.

Regarding the possible issue of gas from the small fields having a Wobbe Index below 51 MJ/m^3, we observed in Option 1 that from 2027 onwards, sufficient H-gas flows are available in the system, at least on a national basis, to absorb the gas produced from the small fields such that the resulting minimum Wobbe Index of 51 MJ/m^3 can be maintained. In this option there will be no extra costs for nitrogen ballasting. However, similar to Option 1 it is at present uncertain whether the existing blending facilities are located correctly.

Additionally, in terms of Wobbe Index this band allows room for the accommodation of a reasonable bandwidth for renewable gases.

5.4 Recommendation

Considering the implications and limitations of the three options assessed above, DNV GL recommends setting the long term quality bandwidth for H-gas at 51 – 55.7 MJ/m^3. In this choice, the bandwidth (4.7 MJ/m^3) is within the 4-5 MJ/m^3 with which millions of appliances function in other EU countries, aligning the distribution practice with those in other countries, and complex and costly gas quality management measures are limited. We remark that a consistent policy for appliance adjustment, using known gas quality, is essential for maintaining this band. Given the general benefits of appliance maintenance for end-user safety, the Dutch government can consider requiring some form of mandatory maintenance, similar to that in other countries, once the switch to H gas has been made.

We recommend updating the proposed notification for the Netherlands for Group E. The existing proposed notification can be found in Appendix A, and the suggested modifications to the notification are given in the same format in Appendix A. We suggest the following modifications:

- In the table we recommend replacing the single value with the following range for Group E: 51,00 – 55.70 MJ/m^3.
- And we recommend altering note g) to: Additional footnote to 'group E'. For group E the safe and reliable operation of gas appliances has to be ensured for the national band of the Wobbe index of 51,00 - 55.7 MJ/m^3 (25/0ºC) by adjusting appliances in the middle of the bandwidth, for example to G20. Upon installation, maintenance and/or repair, the actual gas quality being supplied to the appliance must be known.

In addition, we make the following recommendations regarding near-term distribution gases and possible future modifications of the approval regime.

- If a restriction on the de facto range of higher hydrocarbons is deemed necessary, we then recommend that new test gases and approval procedures be explored, with an eye towards relaxing this restriction for future generations of appliances.
- Regarding potential hydrogen addition, in the short term we recommend exploring the maximum allowable fraction of hydrogen by means of an interchangeability analysis. Here too, with an eye towards the future, we recommend development of a new limit gas and test procedure to guarantee appliance performance for, say, 10% hydrogen without an additional restriction on Wobbe Index.

Additionally, as discussed in Chapter 2, we recommend that the situation regarding the variability in NO_x emissions from certain classes of commercial appliances such as power burners falling under EN 676 be evaluated and a transition route towards 2030 be developed for these appliances, analogous for the necessary change of service for gas engines and industrial equipment. A potential transition route is the development of an active control system for this type of burner that can be integrated afterwards (retrofit) to widen the range of performance for the 51-55.7 MJ/m^3 band[6].

Regarding the potential necessity of blending after the transition to H-gas, to maintain the level of reliability in the transmission system, it is important to ensure that the blending stations and H-gas flows with the right capacity are available at the right place. This does not necessarily need to be the current location of the blending stations. We recommend that GTS evaluates the network implications of the recommendations made for the situation in the year 2030.

[6] We note that such control systems also improve the efficiency of these appliances, providing an additional incentive for the end user.

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APPENDIX A
Notification

Current proposed notification

	Gas Family	Wobbe index (gross) in		Supply pressure in mbar		
		MJ/m^3 or kWh/m^3 (0 °C)	MJ/m^3 or kWh/m^3 (15 °C)	Minimum	Nominal	Maximum
Netherlands	SECOND					
	Group K (f)	43,46 - 45,3 MJ/m^3 (45)		23,7 (46)	25 (46)	30 (46)
	Group E (g)	53,51 MJ/m^3		19 (47)	20 (47)	25 (47)
note						
(f)	Additional footnote to 'group K'. Group K is specific to the Netherlands. It represents gases that have a low Wobbe index and can have a relatively high amount of higher hydrocarbons and carbondioxide. This group is not yet included in appendix B of the EN 437					
(g)	Additional footnote to 'group E'. For group E the safe operation of domestic gas appliances has to be ensured for the national band of the Wobbe index of 47,00 - 55,7 MJ/m3 (0 ºC), either by being adjustable to any specific Wobbe index within this band or by safely accomodating gas from the entire band.					
'(45)	The safe operation of the gas appliances has to be ensured for group K for gases rich in carbondioxide, molecular hydrogen and higher hydrocarbons. Appliances for this gas family must include instructions for converting the appliance to Group E. For non-domestic users in exceptional locations a higher upper Wobbe index may apply, effectively making another gas Group applicable.					
'(46)	The pressures represent the meter inlet pressure for domestic users. The pressure supplied to the appliance is in domestic applications commonly 20-30 mbar. Supply pressures to non-domestic users may be considerably higher.					
'(47)	The pressures represent the meter inlet pressure for domestic users. The pressure supplied to the appliance is in domestic applications commonly 17-25 mbar. Supply pressures to non-domestic users may be considerably higher.					

Proposed update of notification

	Gas Family	Wobbe index (gross) in		Supply pressure in mbar		
		MJ/m^3 or kWh/m^3 (0 ºC)	MJ/m^3 or kWh/m^3 (15 ºC)	Minimum	Nominal	Maximum
Netherlands	SECOND					
	Group K (f)	43,46 - 45,3 MJ/m^3 (45)		23,7 (46)	25 (46)	30 (46)
	Group E (g)	51,00 - 55,70 MJ/m^3		19 (47)	20 (47)	25 (47)
note						
(f)	Additional footnote to 'group K'. Group K is specific to the Netherlands. It represents gases that have a low Wobbe index and can have a relatively high amount of higher hydrocarbons and carbondioxide. This group is not yet included in appendix B of the EN 437					
(g)	Additional footnote to 'group E'. For group E the safe and reliable operation of domestic gas appliances has to be ensured for the national band of the Wobbe index of 51,00 - 55,7 MJ/m3 (0 ºC), by adjusting appliances in the middle of the bandwidth, for example G20. Upon installation, maintenance and/or repair the actual gas quality being provided to the appliance must be known.					
'(45)	The safe operation of the gas appliances has to be ensured for group K for gases rich in carbondioxide, molecular hydrogen and higher hydrocarbons. Appliances for this gas family must include instructions for converting the appliance to Group E. For non-domestic users in exceptional locations a higher upper Wobbe index may apply, effectively making another gas Group applicable.					
'(46)	The pressures represent the meter inlet pressure for domestic users. The pressure supplied to the appliance is in domestic applications commonly 20-30 mbar. Supply pressures to non-domestic users may be considerably higher.					
'(47)	The pressures represent the meter inlet pressure for domestic users. The pressure supplied to the appliance is in domestic applications commonly 17-25 mbar. Supply pressures to non-domestic users may be considerably higher.					

APPENDIX B
Examples of observed gas quality variations in DK, F and UK

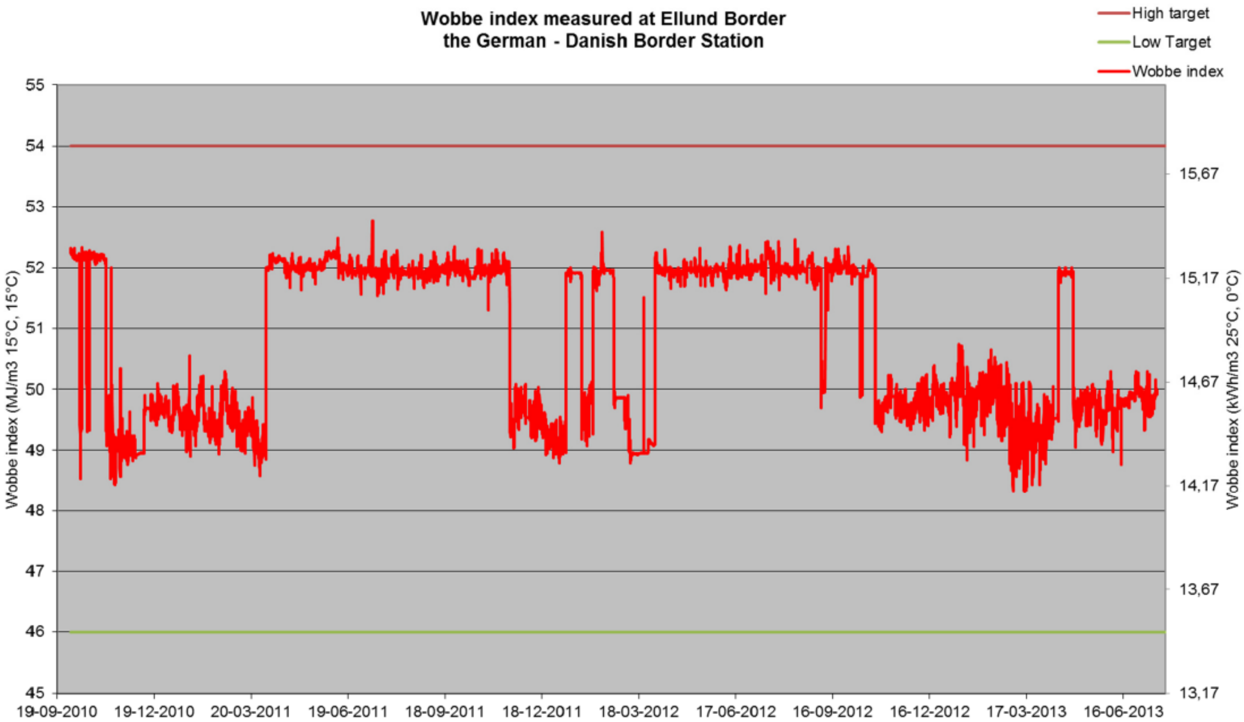

Figure 15: Observed gas quality variations in Denmark

Source: GQ Harmonisation implementation pilot expert meeting, July 19, 2013, supplementary notes DK

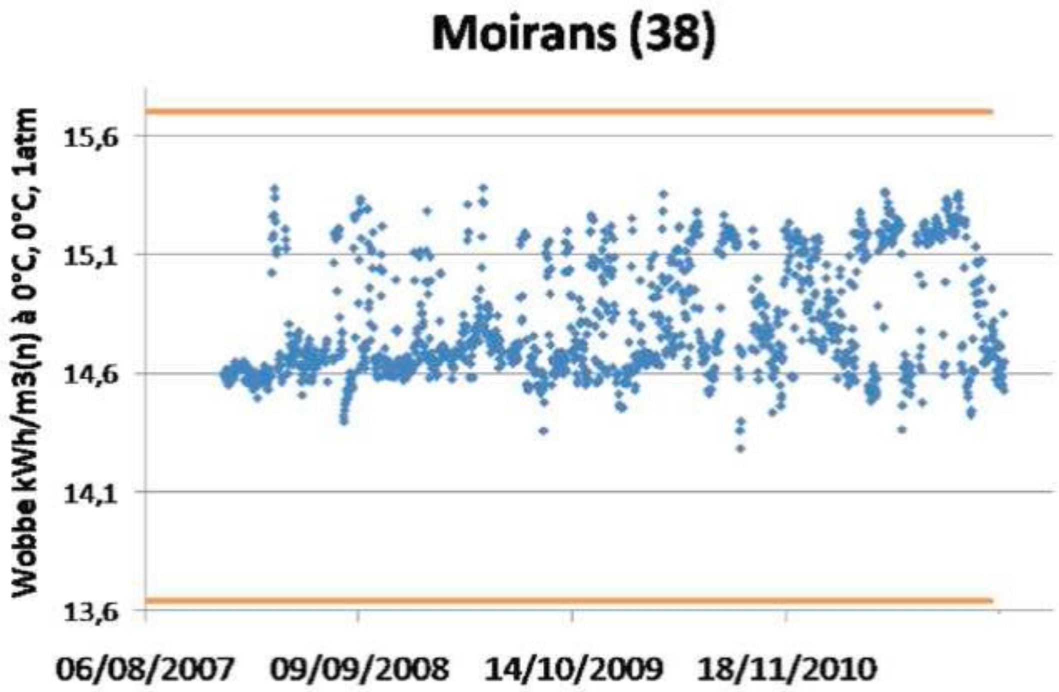

Figure 16: Observed gas quality variations in France

Source: M. de Renty, „Variations de la qualité gaz en France: passé, present et futur…" Colloque „qualité du gaz", Association française du gaz, Paris, 2012

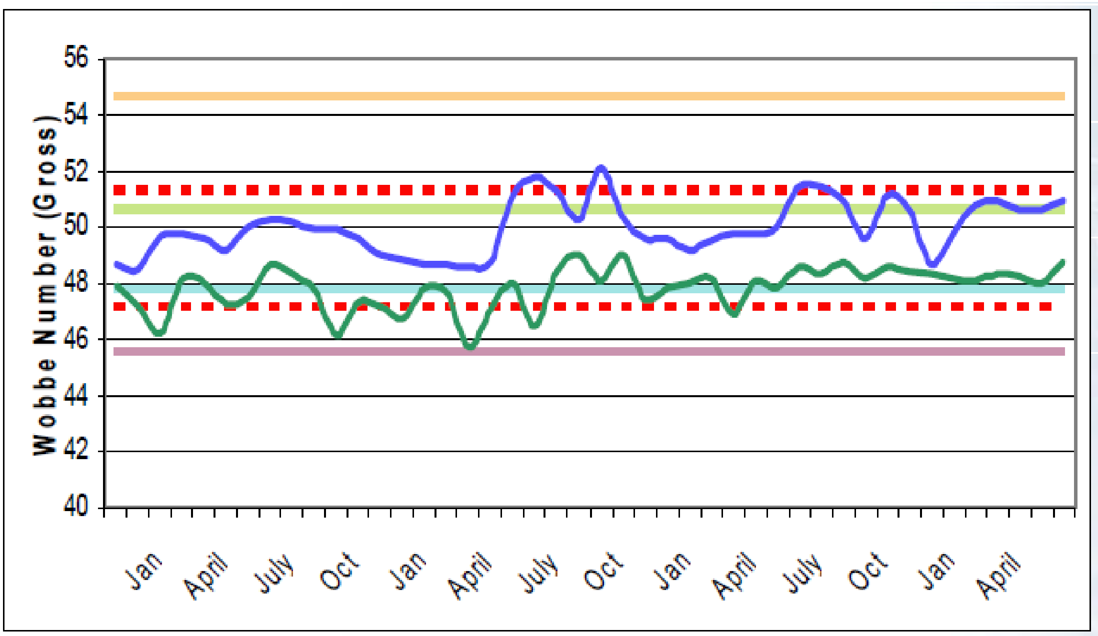

Figure 17: Gas quality UK supply

Source: Figure from a presentation of Baxi (appliance manufacturer) presented by Martin Searle at the Marcogaz Workshop on Gas Quality, St. Denis, December 2005

APPENDIX C
Alternative gas quality management options

Approach:	**Ballasting H-gas with air.**
Short description:	Gas supplied at gas delivery stations at the interface between the gas transmission network and the gas distribution network could be ballasted with air. The goal is to ballast the gas flow with the right volume of air such that the Wobbe Index of the resulting mixture is lowered such that it meets the maximum Wobbe Index the downstream appliances can handle.
Limiting factor:	• Size of the gas delivery station and availability of sufficient space on each site to install a blending facility, control system and air compression.
Costs involved:	CAPEX for blending station at (all) gas delivery stations at the interface between the gas transmission network and the gas distribution network. CAPEX for air treatment (drying) and compression. Also CAPEX for gas chromatographs which are required to measure and safeguard the Wobbe Index of the resulting gas mixture which is supplied to the downstream consumers. OPEX for the operation and maintenance of the blending station.
Advantages:	Disadvantages:
• Air is available free of costs (the conventional alternative is nitrogen which has to be produced using air splitters) • The upper limit gas quality can be specified locally. This allows for a geographical differentiation of gas quality through the Netherlands.	• Necessity of continuous and perpetual ballasting (and blending) burdens the gas infrastructure with a complex gas management system, particularly when considering the variability of the composition of the gas supply. • Recurring operational costs for air drying and compression of air.

Approach:	**Blending off-spec small field gas in richer H-gas flows.**
Short description:	Gas flows outside the gas quality bandwidth cannot be injected into the gas transmission system directly. Gases with a quality higher than the maximum Wobbe Index can be ballasted with nitrogen in order to lower the calorific value and Wobbe Index. This process is referred to as quality conversion (QC). Reverse quality conversion is technically not possible. Alternatively, low calorific value gas can be blended in a calorific higher gas flow to the extent that the quality of the resulting gas flow is above the minimum requirements. So-called gas blending stations are used to blend gas flows in a controlled manner. Gasunie Transport Services has 5 blending stations connecting the low-calorific value and high-calorific value networks.
Limiting factor:	• Blending station location and capacity. • Availability of sufficient rich H-gas flows into which the off spec gas can be blended to make sure that the quality of the resulting gas stream is still within the gas quality bandwidth. However, expectation is that the gas quality of H-gas import streams is well above 50 MJ/m^3 (see section 3.2.2). Also the capacity of the small fields will drop significantly (see Figure 11). This could provide (sufficient) room for accommodating gases outside the newly considered H-gas Wobbe Index bandwidth.
Costs involved:	CAPEX for potentially additionally required blending station capacity, stranded assets in case certain pipeline sections which were previously used for the small field gases cannot be used anymore.
Advantages:	Disadvantages:
• Blending stations provides an active means for the management of gas quality in the gas transmission network. • Limited OPEX for operating a blending station.	• The existing blending station capacity might not be at the right location in the network.

Approach:	**Isolating off spec gas in separate part of the gas transmission network and supplying to a dedicated group of consumers.**
Short description:	Off spec gas which cannot be injected in the main H-gas gas transmission network can be transmitted in dedicated pipelines and supplied to a dedicated group of industrial consumers.
Limiting factor:	The consumer group Industrial consumes a total volume of about 10-13 bcm per year. Off spec gas is predominantly produced in the northern part of the Netherlands (small fields/entry points of NGT, Groningen/Friesland and Ommen). The number of industrial consumers in the northern part of the Netherlands is limited. The number of industrial consumers and their capacity might not be high enough to absorb the off spec capacity and volume of gas, this could mean that the gas has to be produced at a lower level over a longer period of time.
Costs involved:	No specific costs identified upfront.

Advantages:	Disadvantages:
• Industrial consumers are a relative small group of consumers (58 entities with in total 90 connections) with a large capacity. The annual consumption of the consumer group Industrials amounted to a volume of around 18 bcm[4] [number to be confirmed]. • With this option, the conversion of other G-gas consumers to H-gas can also be delayed. • Industrial consumers typically have a base-load consumption profile. This matches the profile of gas production, which is characterized by high operating hours (typically 77%). • These customers generally have highly skilled representatives. Bilateral gas quality arrangements can be made with this selected group of customers, particularly those who already are set up to accept gases on the lower part of the Wobbe band.	• Industrial consumers are spread over the country, but with a high concentration in the Rijnmond area and in IJmond, Delfzijl/Eemshaven, Limburg and Zeeland[7]. Except for Delfzijl/Eemshaven this is not the region where off spec gas is produced. The small fields/entry points of NGT, Groningen/Friesland and Ommen, all in the northern part of the Netherlands.

[7] Source: Inventarisatie gevolgen transitie nieuw aardgas voor Hgas gebruikers, Projectbureau Nieuw Aardgas, 2011. http://www.rvo.nl/sites/default/files/bijlagen/Inventarisatie%20gevolgen%20transitie%20nieuw%20aardgas%20voor%20Hgas-gebruikers.pdf

Approach:	**In-situ production of electricity from off-spec gas**	
Short description:	If off-spec gas cannot be accommodated in the gas transmission network it could be an option to consume it on-site and generate electricity. This approach is sometimes considered in tail-end gas production where the well head pressure becomes too low and installing gas compression is economically not viable.	
Limiting factor:	Availability of high voltage electricity transmission grid connection, emission limitations in the particular area, depending on the total electricity production per year (and corresponding intake of natural gas).	
Costs involved:	CAPEX of power generation facility and connection to electricity transmission grid.	
Advantages:		Disadvantages:
• Gas production can continue and the gas field can still be commercialized, generating revenue for the gas producer. • Centralized (large scale) investments in the gas transmission network are avoided.		• Setting up the commercial arrangements with producer might be challenging, in particular since the existing regulatory framework does not foresee such a set-up. • Depending on the location, it might not be possible to use waste heat from power generation.

<table>
<tr><td>Approach:</td><td colspan="2">In-situ production of LNG</td></tr>
<tr><td>Short description:</td><td colspan="2">If the quality of the gas produced from a field is such that it cannot enter the gas transmission network it could be an option to produce LNG directly onsite. The produced LNG is then made available for use as a transportation fuel, for example for ships or trucks.</td></tr>
<tr><td>Limiting factor:</td><td colspan="2">The local development plan (in Dutch: bestemmingsplannen) and permits.</td></tr>
<tr><td>Costs involved:</td><td colspan="2">CAPEX for liquefaction plant and OPEX for operating the plant.</td></tr>
<tr><td colspan="2">Advantages:</td><td>Disadvantages:</td></tr>
<tr><td colspan="2">Avoiding unmanageable gas quality issues in the network.
Avoiding costly investments in the gas transmission network either in the form of connecting pipelines or nitrogen plants in case quality conversion is required.
For the producers this could also be attractive. LNG for transportation will compete with conventional transportation fuels. The fuel price in this segment might be more attractive compared to prices on the conventional gas market.</td><td>Energy conversion losses: energy is consumed in the production of LNG.
Potentially higher CAPEX for the producer compared to conventional gas production and injection in the gas transmission grid (in case the costs for grid connection are not socialized).</td></tr>
</table>

<table>
<tr><td>Approach:</td><td colspan="2">(Temporary) Access restriction for off-spec gas</td></tr>
<tr><td>Short description:</td><td colspan="2">The Gas Act – article 54b provides the room for the network operator to set requirements for the intake of gas in the network from an effectiveness perspective (in Dutch: doelmatingheid). Such a requirement could be an access restriction regarding gas quality. The access restriction could have temporary nature (only restricting access in case of congestion).</td></tr>
<tr><td>Limiting factor:</td><td colspan="2">-</td></tr>
<tr><td>Costs involved:</td><td colspan="2">No immediate direct costs, though revenue foregone for Gasunie Transport Services (reduced network entry capacity sales).</td></tr>
<tr><td colspan="2">Advantages:</td><td>Disadvantages:</td></tr>
<tr><td colspan="2">Avoiding unmanageable gas quality issues in the network.
Avoiding investments in the gas transmission network.</td><td>Lowering of produced volumes from gas fields, delay in revenue for producers.
Might be undesirable from an economic and gas market perspective.
If access is interrupted frequently (e.g. every other day), this can have negative effect on the overall yield of the field over the entire life cycle. More gradual variations (e.g. seasonal production profile) should provide no problem.</td></tr>
</table>

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