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ASSESSMENT OF THE IMPACT OF HYDROGEN INJECTION AT CADENT'S NTS OFFTAKES EXECUTIVE SUMMARY

BACKGROUND

Cadent Gas wish to investigate the impacts of injection of hydrogen into its local transmission and distribution systems. In particular it wishes to understand the interaction between hydrogen, natural gas and biomethane – both in the short term, as biomethane production continues to grow in importance and hydrogen injection commences, and in the longer term, when natural gas is likely to be the minor gas conveyed and biomethane and hydrogen dominate. The impacts of specific interest are those arising from the requirements of the Gas (Calculation of Thermal Energy) Regulations and the Gas Safety (Management) Regulations. The GCOTER govern consumer billing and Cadent require an assessment on how location of injection (e.g., at an NTS offtake or further down the pressure tier) affects impacts for different injection rates. The GSMR govern safety impacts and Cadent require an assessment of the amount of hydrogen that can be added before the lower limit of Wobbe index prevents further injection and hence the impact of injection location.

CONCLUSIONS

a) Hydrogen injection at the NTS offtake offers a means of achieving conveyance of a natural gas blend containing up to 20% hydrogen within the existing regulatory framework of the GCOTER and within the GSMR, providing the existing maximum limit on hydrogen content can be modified to allow conveyance from 0.1% to up to 20% hydrogen.

b) Capping of FWACV is the principal constraint on the proportion of hydrogen than can be accommodated. The proportion of hydrogen that can be blended varies from around 4% when a relatively small proportion of LDZ energy is supplied as blend, to up to 20% when around 80% or more of LDZ energy is supplied as blend. As a general rule therefore, blend should dominate the amount of energy supplied to a given LDZ. This can be achieved through supplying blend through multiple offtakes or though one large offtake.

c) Adding a significant proportion of LDZ energy as blend reduces the FWACV and hence reduces risk of capping. For this assessment, the energy flows into both LDZs were for those in 2020 and so were not optimised for hydrogen production. Optimising NTS offtake flows is likely to result in a significant increase in hydrogen injection capacity of LDZs.

d) FWACV capping is more of a constraint if the CV of natural gas supplies into an LDZ vary significantly. In such situations, the reduction of FWACV is not so great particularly if hydrogen is blended with lower CV supplies. This is seen with EM LDZ, where the range of CV is greater than with NW LDZ. As a general rule hydrogen injection is more effective if added to the highest CV source.

e) The lower Wobbe index (WI) limit of the GSMR can constrain the proportion of hydrogen that can be injected to less than 20%, even if blend is supplying in excess of 80% of LDZ demand. Such GSMR constraints occur if the WI of the natural gas in the LDZ is closer to the GSMR lower limit and occurs more frequently with NW LDZ than with EM LDZ. A future proposed reduction in the lower WI limit in the GSMR would reduce the incidence of this constraint in the NW LDZ.

f) Because hydrogen injection at the NTS offtakes reduces the FWACV, the enrichment requirements for existing and future biomethane injection projects are likely to be reduced. However, it is unlikely that the need for enrichment would be removed completely, so although operating cost can be reduced, the capital investment for enrichment plant for future projects is unlikely to be avoided.

g) In principle, existing metering systems at the NTS offtakes are not likely to be compromised by injection of hydrogen, although upgrade of equipment will be required. Future plans for upgrading such sites will need to be designed to accommodate hydrogen injection.

h) Hydrogen injection adds an additional layer of complexity to network control and operation and better tools are likely to be required. The gas transporter will need to exercise more control over balancing of when, where and how much hydrogen is injected against FWACV and GASM constraints. This will need significant discussion and agreement within the industry.

ASSESSMENT OF THE IMPACT OF HYDROGEN INJECTION AT CADENT'S NTS OFFTAKES

1 INTRODUCTION

Cadent Gas wish to investigate the impacts of injection of hydrogen into its local transmission and distribution systems. In particular it wishes to understand the interaction between hydrogen, natural gas and biomethane – both in the short term, as biomethane production continues to grow in importance and hydrogen injection commences, and in the longer term, when natural gas is likely to be the minor gas conveyed and biomethane and hydrogen dominate. The impacts of specific interest are those arising from the requirements of the Gas (Calculation of Thermal Energy) Regulations and the Gas Safety (Management) Regulations. The GasCOTE regulations govern consumer billing and Cadent require an assessment on how location of injection (e.g., at an NTS offtake or further down the pressure tier) affects impacts for different injection rates. The GSMR govern safety impacts and Cadent require an assessment of the amount of hydrogen that can be added before the lower limit of Wobbe index prevents further injection and hence the impact of injection location.

Dave Lander Consulting was commissioned by Cadent to assess the likely impacts of hydrogen injection and this report details the results from and conclusions to be drawn from this study.

2 AIMS AND OBJECTIVES OF THIS STUDY

The aim of the study is to assess the operational impacts of hydrogen injection under the existing regulatory regime. The objectives are as follows:

a) To assess the impacts and determine the likely operational envelope for two of Cadent's Local Distribution Zones (LDZs), given the regulatory constraints. The two LDZs assessed were the North West (NW) and East Midlands (EM).

b) To provide answers to specific questions posed by Cadent relating to hydrogen injection.

3 REGULATORY CONSTRAINTS ON HYDROGEN INJECTION

There are two regulations that govern gas quality of gas conveyed in Great Britain's gas transmission and gas distribution systems: the Gas (Calculation of Thermal Energy) Regulations and the Gas Safety (Management) Regulations.

3.1 THE GAS (CALCULATION OF THERMAL ENERGY) REGULATIONS

The GCOTER govern how gas consumers are billed and deal specifically how the quantity of gas consumed by a particular consumer is determined (as a volume and how this is converted to a volume at agreed reference conditions) and then converted to an amount of energy by multiplication by a gross calorific value. Methods for volume conversion and determination of calorific value are prescribed within the GCOTER.

The majority of gas consumers within GB are billed on the basis of a charging area calorific value, i.e., consumers (or more specifically their metering points) are assigned to a one of thirteen[1] charging areas, all of whom are deemed to have received gas of the same calorific value. Since the 1997 amendment to the GCOTER, the calorific value used to calculate the amount of energy consumed at each meter point is an arithmetic average of daily Flow Weighted Average CVs (FWACVs) for a given charging period. Each daily FWACV is computed from the total daily energy supplied to a charging area divided by the daily volume supplied to that charging area:

[1] Excluding the six physically-separate Scottish Independent Undertakings and Stornaway and Stranraer networks.

$$FWACV = \frac{E_{24}}{V_{24}} \quad \text{Equation (1)}$$

Where E_{24} and V_{24} are the daily energies and daily volumes supplied into each charging area. E_{24} and V_{24} are the net flows into the charging area, i.e., the sum of all the flows into the charging area minus any flows out of the charging area.

The daily charging area CV is defined in Regulation 4A of the GCOTER and in particular it requires that the daily charging area CV shall be the lower of:

- the FWACV
- the lowest of the daily average CVs for any of the input points to the charging area (generally referred to as the Lowest Source CV, or LSCV) **plus 1 MJ/m^3**.

The limitation that the daily charging area CV shall be no more 1 MJ/m^3 more than the LSCV is known as the "FWACV cap" and provides a driver on the industry to limit the extent of over-billing of individual gas consumers that receive gas with a lower calorific value than the daily average CV. Application of the FWACV cap essentially results in under-recovery of billing income for the Gas Shipper/Suppliers.

One consequence of the FWACV cap is the difficulty in accommodating low CV sources of gas and in particular gases from unconventional sources, such as biomethane and as a result, injection of biomethane usually requires its enrichment by adding propane, which is contrary to the long-term goal of decarbonising the GB gas networks. In a similar way, adding hydrogen to natural gas produces a gas of lower CV and so the FWACV cap provides a constraint on how much hydrogen can be added to natural gas.

Note that the GCOTER refers to the term "charging area" and the charging areas employed by the industry on coming into force of the GCOTER were essentially the thirteen LDZs. The two terms are therefore interchangeable for the purpose of this study, although future changes to GB billing could employ alternative, different charging areas.

Note that Regulation 4A(1) paragraph (b) of the GCOTER permits application of the cap to the daily average CV of a co-mingled point, provided it can be shown that no gas is conveyed to consumers before co-mingling. This therefore means that injection of hydrogen, which has a CV of 12.1 MJ/m^3, would not result in a charging area CV of 12.1 + 1.0 = 13.1 MJ/m^3, provided that the CV of the blended mixture of natural gas and hydrogen at the NTS offtake is determined and it can be demonstrated that no consumer receives gas before blending.

3.2 THE GAS SAFETY (MANAGEMENT) REGULATIONS

Regulation 8 of the GSMR prescribes the quality of gas conveyed by gas transporters in their network and gas quality is specified by reference to Schedule 3 of the GSMR. The two gas quality parameters relevant to this study are the maximum hydrogen content, which is currently set at no more than 0.1% (mol/mol), and the Wobbe index (WI), which is set at no less than 47.2 MJ/m^3, under normal conditions[2].

The maximum hydrogen content is an artificial limit, in the sense that it was set at this value when the GSMR were published in 1996 as a convenience in specifying interchangeability of gas by reference to a two-dimensional "interchangeability diagram", as opposed to Dutton's three dimensional "interchangeability volume" employed by the British Gas Corporation prior to its privatisation. At the time, natural gases containing hydrogen were not employed and expected to arise in the future mainly from manufacture of Substitute Natural Gases.

[2] Schedule 3 permits gas of lower WI to be conveyed (no more than 46.5 MJ/m^3) if necessary to prevent a supply emergency.

In practice it is felt that natural gas blends containing up to 20% hydrogen can be safely distributed and utilised without need to replace domestic appliances and relatively minor adjustment of many commercial and industrial appliances. The NIC project HyDeploy aims to demonstrate the case for blends up to 20% hydrogen and this study assumes that regulatory change to permit gas transporters to convey such blends will be agreed and made.

The lower WI limit of 47.2 MJ/m^3 is therefore the main constraint within the GSMR on addition of hydrogen. Hydrogen has a WI of 45.9 MJ/m3 and hence the amount of hydrogen that can be added will be limited by the WI of the natural gas itself. Natural gas with WI close to the lower limit will be able to accommodate only small amounts of hydrogen, whereas those with higher WI can accommodate larger amounts.

There are plans to revise the GSMR and one such change is to remove Schedule 3 and amend Regulation 8 appropriately so that it refers to a separate gas quality specification. The gas quality specification is likely to be an IGEM standard (IGEM/GL/10) and drafting and approval of IGEM/GL/10 is currently in progress. One proposed change is for the lower WI limit to be revised downwards from 47.2 to 46.5 MJ/m^3.

4 METHODOLOGY OF ASSESSMENT

4.1 DATA SOURCES

Data files produced by the Danint software that is resident on each of the Cadent's NTS offtake sites were employed for this study. Two data sources were employed for this study:

- The Danint "DAT" files, containing every gas composition measured by the Ofgem-approved gas chromatograph (typically every 4 minutes) during each gas day.
- The Danint "EOD" files, containing the daily average[3] CV, the daily average relative density (RD), the daily energy and the daily volume for each gas day.

Data was supplied by Cadent for every gas day over the period 01/01/2020 – 31/01/2020 and data extracted into a spreadsheet model using a bespoke Excel macro designed for this purposes.

In order to limit file size, the gas compositions extracted from the DAT file were limited to every tenth analysis, which corresponds to analyses every 40-50 minutes during each gas day. DAT files were extracted only for two offtakes: One offtake in the NW LDZ and one offtake in the EM LDZ.

4.2 ESTIMATION OF GSMR CONSTRAINTS ON MAXIMUM AMOUNT OF HYDROGEN THAT CAN BE ADDED

The DAT file provides gas composition and allows the WI to be calculated for the natural gas and after addition of hydrogen. In order to estimate the maximum amount of hydrogen that can be added, for each gas composition record the hydrogen content was adjusted (from zero) until a WI of either 47.2 MJ/m^3 or 46.5 MJ/m^3 was achieved. This allows an estimate of how existing gas quality in the two LDZs (NW and EM) may constrain the maximum amount of hydrogen that can be added.

4.3 ESTIMATE OF CONSTRAINTS ON THE DAILY AMOUNT OF HYDROGEN THAT CAN BE ADDED

The EOD file does not contain gas compositional data and so key properties of CV, RD and WI after addition of hydrogen have to be calculated from interpolation between the properties of the natural

[3] The GCOTER prescribes that daily average CV at each input point to the charging area is calculated as the arithmetic average of all "valid" CV records determined for that input point. Valid CV records are those in which the CV determination device is not in alarm and for which gas flows past the sample point. The averaging process is carried out at the end of each gas day by the EODAVE module of the Danint software suite. The same process is employed by EODAVE in averaging RD.

gas and pure hydrogen. For calorific value, the error associated with linear interpolation is relatively small, but for WI it is extremely large. This is illustrated in Figure 1. WI was therefore estimated by calculating the interpolated CV and dividing by the interpolated RD. This resulted in relatively small errors in both CV and WI, and this is illustrated in Figure 2.

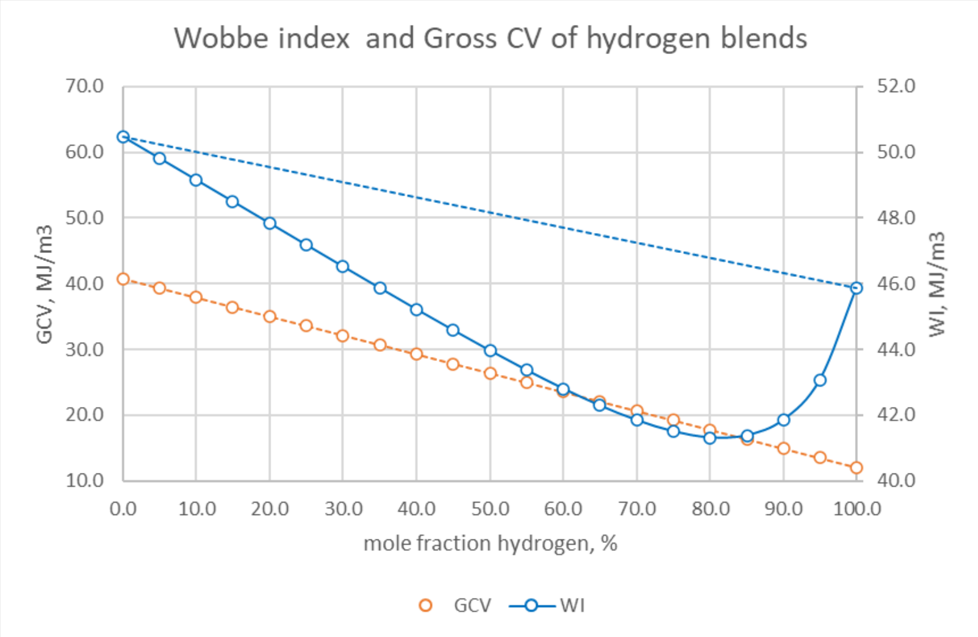


Figure 1: Linear interpolation of CV and WI from the properties of natural gas and pure hydrogen. The open circles are the correctly-calculated properties, and the dotted lines correspond to linear interpolation.

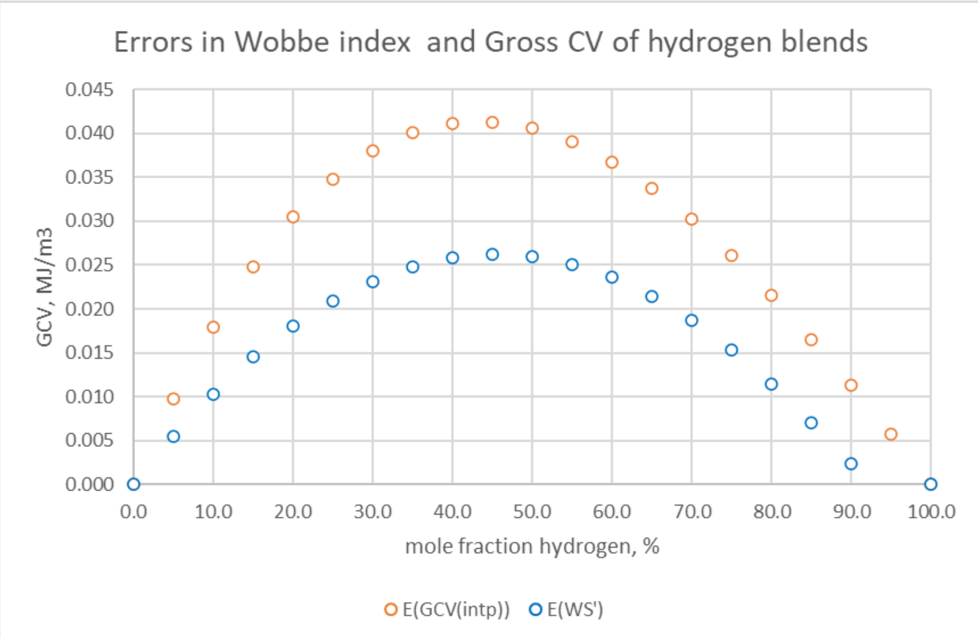


Figure 2: Errors in WI and CV resulting from linear interpolation method.

The above methodology permits an estimate of daily average CV and daily average WI for each gas day in the year 2020 for blends with a given hydrogen content. In order to establish the constraints on how much hydrogen can be added for each gas day in 2020 a spreadsheet model was constructed that established for each gas day:

a) The daily volumes, daily energies, the daily average CV and the daily average WI for each gas day at the relevant charging area inputs to the two LDZs.

b) The FWACV for each gas day, based on the LDZ energies and the LDZ volumes using Equation (1).

c) The LSCV and hence the CV at which the FWACV comes in to force (i.e., LSCV plus 1 MJ/m^3)

The spreadsheet model calculates the above properties for two cases: the existing situation (no hydrogen injection) and for hydrogen injected into one or more NTS offtakes. In order to estimate the maximum amount of hydrogen that can be added in a given gas day hydrogen was progressively added[4] until either of the following situations occurred:

- Capping of FWACV occurred (i.e., FWACV-LSCV = 1.0 MJ/m^3), or
- The lowest (daily average) WI reached the GSMR lower limit of 47.2 MJ/m^3, or
- The hydrogen content reached 20%

For cases in which hydrogen was added at more than one NTS offtake, the proportion of hydrogen was assumed to be the same at each offtake. This is a simplification adopted in the model, although in practice, injection could be operated independently.

5 SIMPLIFICATIONS AND LIMITATIONS OF THE STUDY

The above methodology necessarily introduces simplifications and limitations, and these are summarised below:

a) The analysis is based on daily average property data and hence within-day variation is not accounted for.

b) Hydrogen mole fraction is assumed to be the same at each NTS offtake where it is injected. As discussed above, in practice hydrogen injection could be controlled independently at each NTS offtake.

c) In calculation of FWACV, exit flows from the LDZ were ignored. The principle source of exit flows are inter-LDZ transfers, and large industrial users billed using a "site-specific" CV. The number and size of such inter-LDZ transfers is relatively small and were considered to be not relevant with respect to the GCOTER. The main impact of inter-LDZ flows is in the allocation of transportation revenue to the correct GDN. Six inter-LDZ flows were identified in 2005 for metering upgrade because the flows involved different GDNs. None of these flows involved NW LDZ or EM LDZ, although attention is drawn to the possible existence of other inter-LDZ flows between LDZs managed by Cadent. Similarly large industrial users are considered to be relatively small and not relevant.

d) Gas exiting the NTS at each offtake is assumed to contain no hydrogen. National Grid Gas are considering hydrogen addition and so the extent to which natural gas at the NTS offtake is hydrogen free will depend on progress in adding hydrogen at NTS entry points.

e) Energy demand is assumed to be the same with and without hydrogen addition. This effectively assumes that the efficiency of appliances consuming gas remains the same. This is likely to be so for domestic and commercial heating appliances, but for some industrial processes it may not always be so, particularly non-heating related processes (e.g., carbon fibre manufacture for brake linings).

[4] Hydrogen addition was automated using an Excel macro that searched for the above end point using a tolerance of 0.1% hydrogen, i.e., hydrogen was increased in wider, then progressively narrower increments of 0.1% and once one of the above criteria was met the hydrogen content was decreased by 0.1%.

6 HYDROGEN INJECTION IN NW LDZ

6.1 INPUT POINTS TO NW LDZ

Nine input points to the NW LDZ were included in the model: Blackrod, Eccleston, Holmes Chapel, Lupton, Mickle Trafford, Partington, Samlesbury, Warburton and Weston Point.

6.2 GSMR CONSTRAINTS ON MAXIMUM AMOUNT OF HYDROGEN THAT CAN BE ADDED

For NW LDZ, the existing GSMR lower limit in WI of 47.2 MJ/m^3 constrained hydrogen injection for 2004 out of 14,265 records. This suggests that the GSMR might constrain hydrogen to less than 20% hydrogen for around 14% of the time (ignoring FWACV capping)

If the GSMR lower limit in WI were changed to 46.5 MJ/m^3, then there would be no GSMR constraint in hydrogen addition (other than the proposed 20% limit being examined under the HyDeploy project).

This is illustrated in Figure 3 below, which plots CV against √RD. Such plots permit visualisation of both CV and WI, which corresponds to a straight line on the plot. The dotted red lines correspond to the existing GSMR upper and lower limits in WI; the dotted purple lines correspond to the new values proposed in IGEM/GL/10.

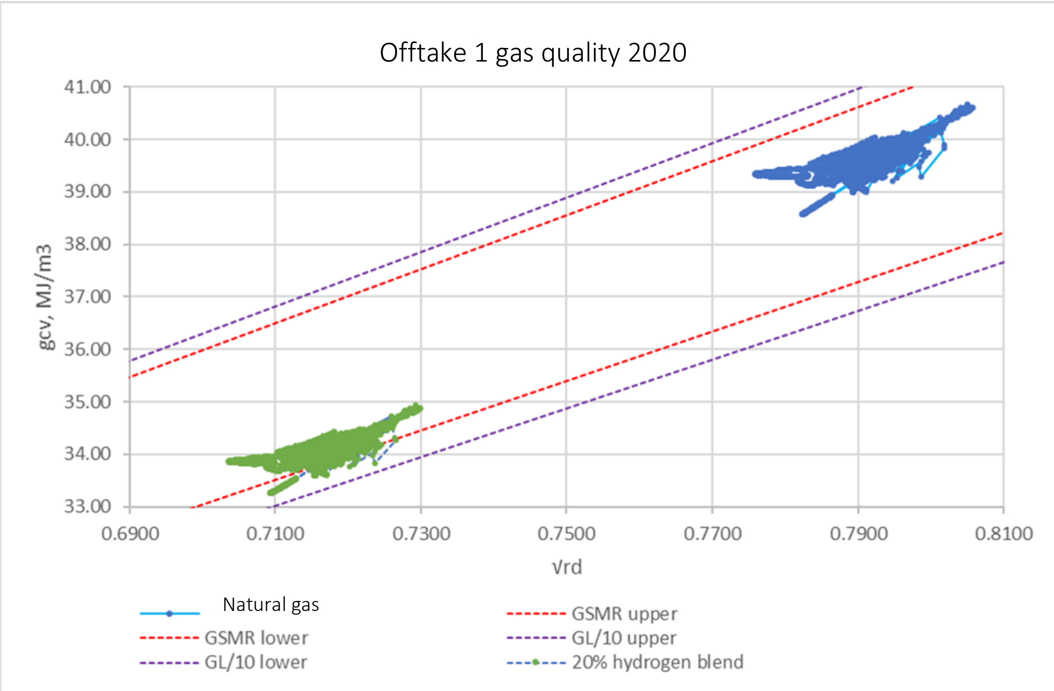


Figure 3: Gas quality at an offtake with (green circles) and without (blue circles) 20% hydrogen addition.

6.3 ESTIMATE OF CONSTRAINTS ON THE DAILY AMOUNT OF HYDROGEN THAT CAN BE ADDED

6.3.1 HYDROGEN ADDITION AT TWO NTS OFFTAKES:

Figure 4 shows the proportion of hydrogen that could have been added at 2 NTS offtakes during 2020. For much of the year, hydrogen is constrained to around 5%. For some periods in Summer higher amounts of hydrogen would have been possible when blend becomes a higher proportion of LDZ energy.

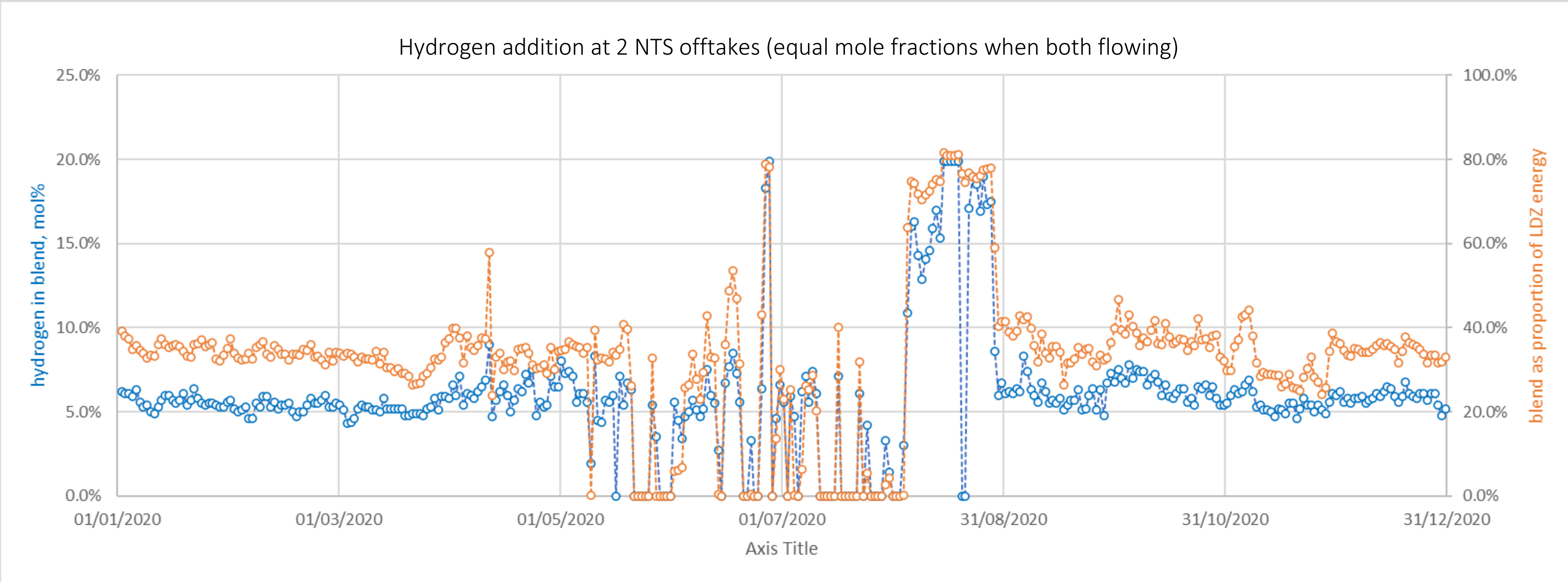


Figure 4: Hydrogen addition at 2 NTS offtakes. Blue open circles are the proportion of hydrogen that can be added; brown open circles are the proportion of daily LDZ energy flowing as blend into the LDZ. [LDZmodel30-2]

The relationship between proportion of hydrogen that can be added and proportion of LDZ energy as blend is more clearly seen in Figure 5.

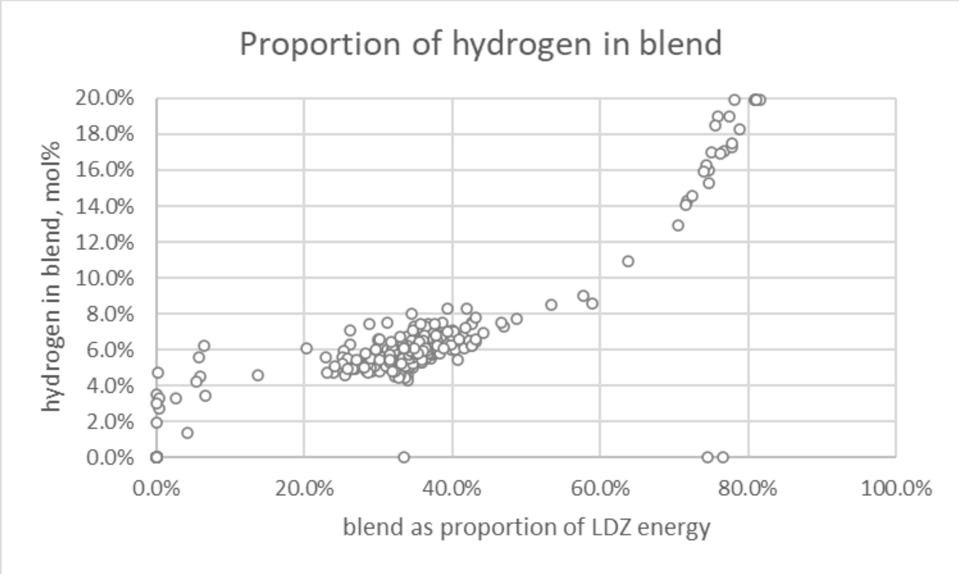


Figure 5: Proportion of hydrogen that can be added at 2 NTS offtakes against proportion of LDZ energy flowing as blend. [LDZmodel30-2]

6.3.2 HYDROGEN ADDITION AT SIX NTS OFFTAKES

For this situation, because blend comprises a higher proportion of LDZ energy a greater proportion of hydrogen, up to the maximum of 20% can be accommodated without capping the FWACV.

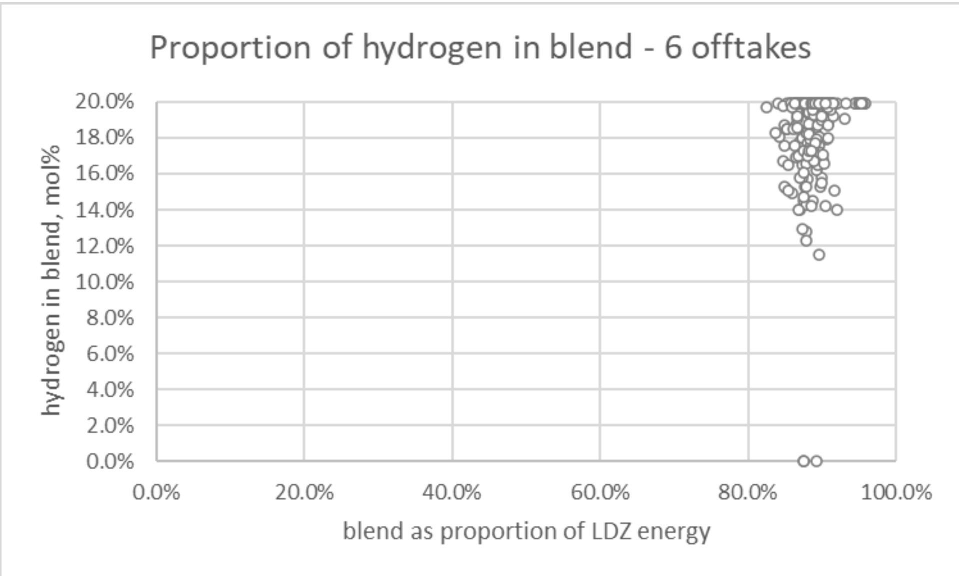
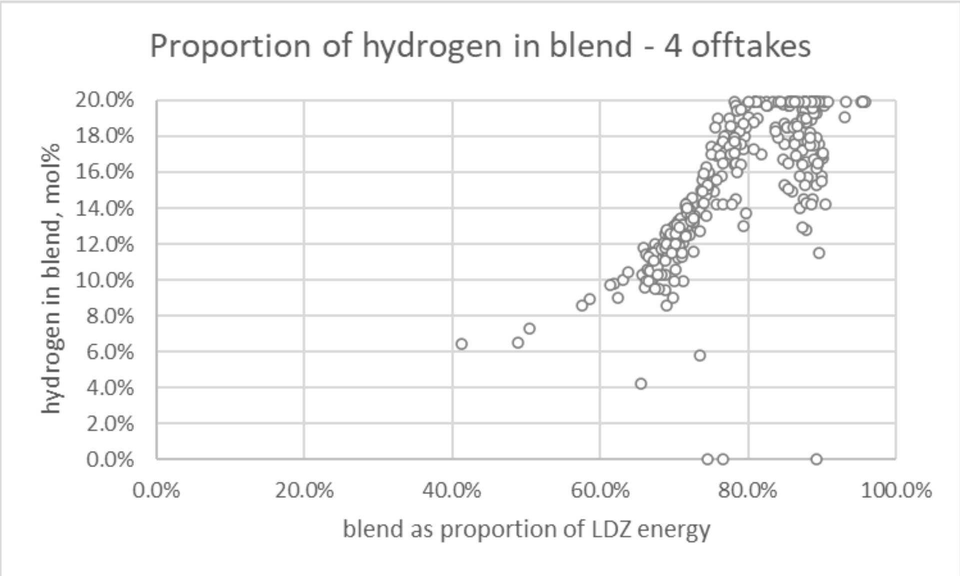


Figure 6: Proportion of hydrogen that can be added at six NTS offtakes against proportion of LDZ energy flowing as blend. [LDZmodel30-6]

6.3.3 HYDROGEN ADDITION AT FOUR NTS OFFTAKES

Injection at four NTS offtakes was also investigated.

Figure 7: Proportion of hydrogen that can be added at four NTS offtakes against proportion of LDZ energy flowing as blend. [LDZmodel30-4_6431]energy flowing as blend. [LDZmodel30-4_6431]



A composite plot showing hydrogen injection at 2, 4 and 6 NTS offtakes is shown in Figure 8 below.

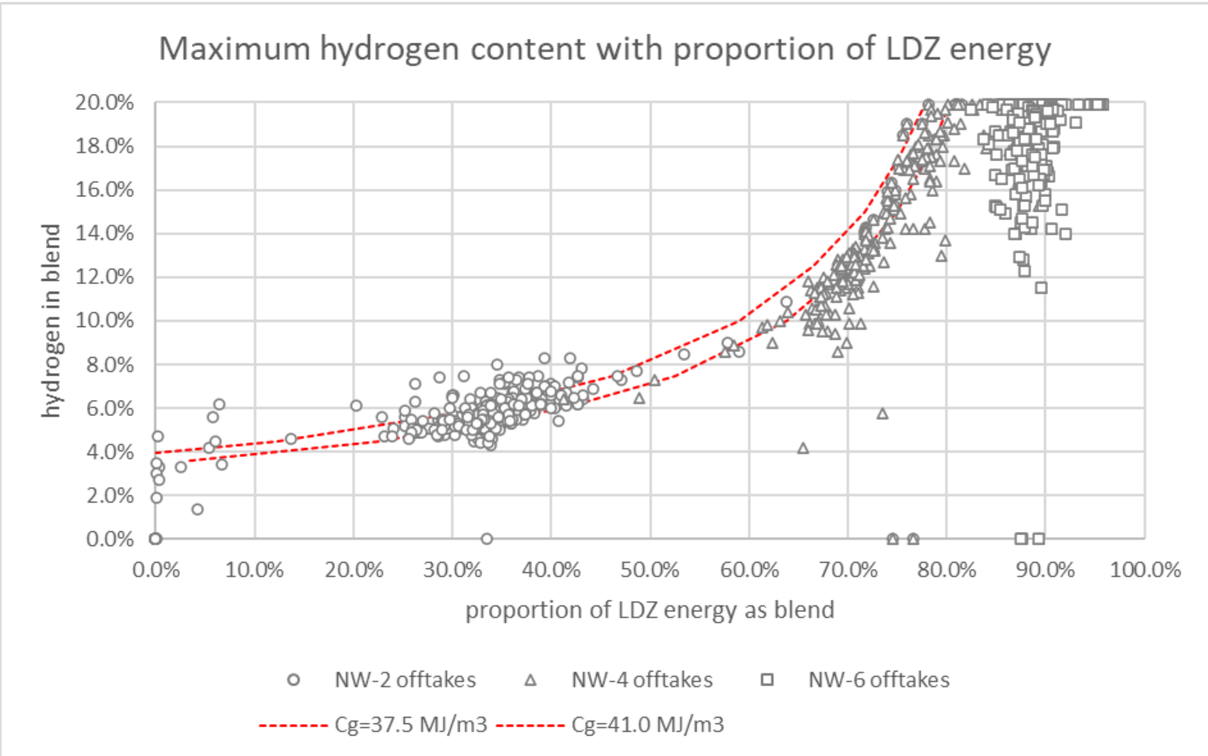


Figure 8: Composite plot of injection of hydrogen into NW LDZ at 2, 4 and 6 NTS offtakes [Summary_NW-EM_sort]

If it assumed that the calorific value of all natural gas in an LDZ is the same, then it can be demonstrated that the proportion of hydrogen in the blend achievable at the FWACV cap is related to the proportion of LDZ energy that is blend is given by Equation 2:

$$z = \frac{xC_h + (1-x)C_g}{xC_h + (1-x)C_g + 1} \times \left(1 - \frac{1}{x(C_g - C_h)}\right)$$ Equation (2)

Where z = proportion of LDZ energy that is blend
x = proportion of hydrogen in blend
Cg is the CV of natural gas
Ch is the CV of hydrogen

The red dashed lines in Figure 8 show plots of Equation (2) assuming that the CV of natural gas is 37.5 MJ/m^3 and 41.0 MJ/m^3. The plots are relatively insensitive to CV and demonstrate that a higher proportion of hydrogen can be accommodated in the blend if the blend itself supplies a higher proportion of LDZ energy.

The reason that higher proportions of LDZ energy supplied blend allows a greater proportion of hydrogen is that when blend is a high proportion of LDZ energy the FWACV is reduced. As a result, although adding hydrogen reduces the LSCV, the difference between FWACV and LSCV remains less than 1.0 MJ/m3 and a higher proportion of hydrogen can be accommodated in the blend without triggering a FWACV cap. This is illustrated in Figure 9, which is a composite plot of the change in FWACV as the proportion of LDZ energy supplied as blend increases. The data is for injection into NW LDZ at 2, 4 and 6 NTS offtakes.

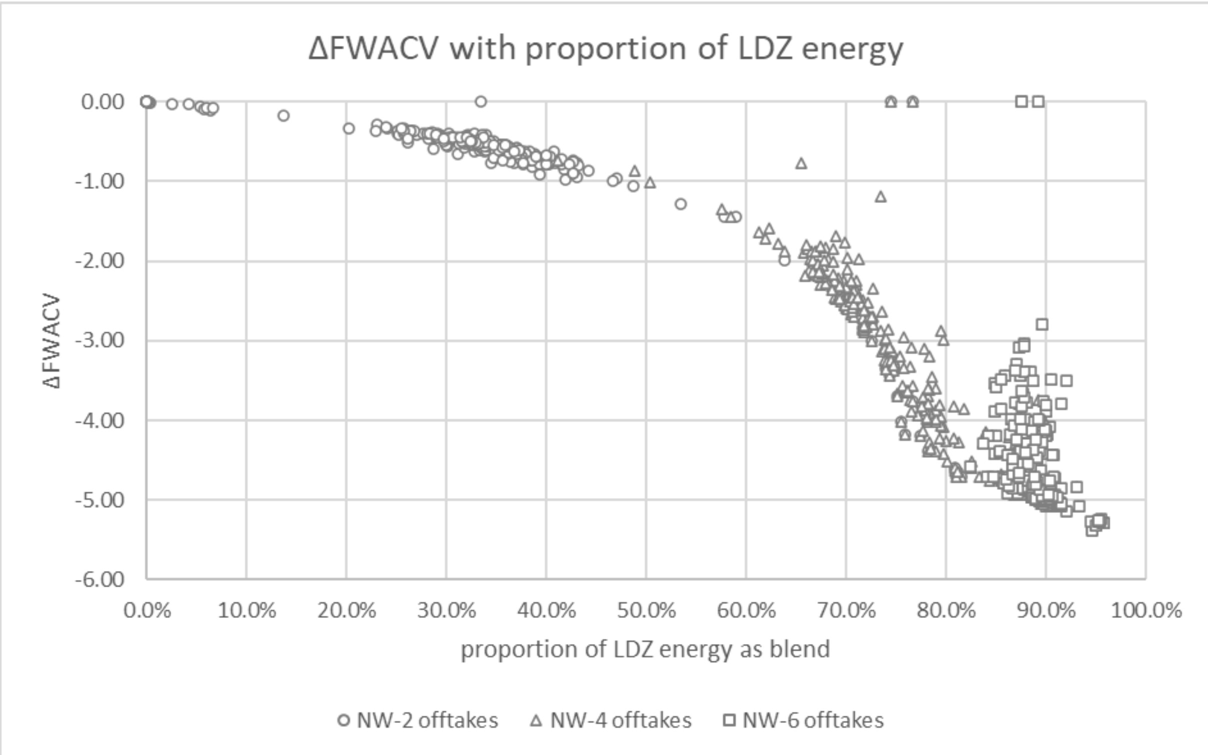


Figure 9: Composite plot of change in FWACV as the proportion of LDZ energy as blend increases [Summary_NW-EM_sort]

6.4 PRINCIPLE CAUSE OF CONSTRAINT IN ADDITION OF HYDROGEN – NW LDZ

The principal cause of constraint in the proportion of hydrogen that can be added are illustrated in Figure 10, which shows the composite plot of data for all three scenarios of addition (injection at 2, 4 and 6 NTS offtakes). Data points are colour coded by principle cause: red points correspond to FWACV capping, blue points correspond to the lower WI limit of the existing GSMR, and green points correspond to the proposed 20% hydrogen limit.

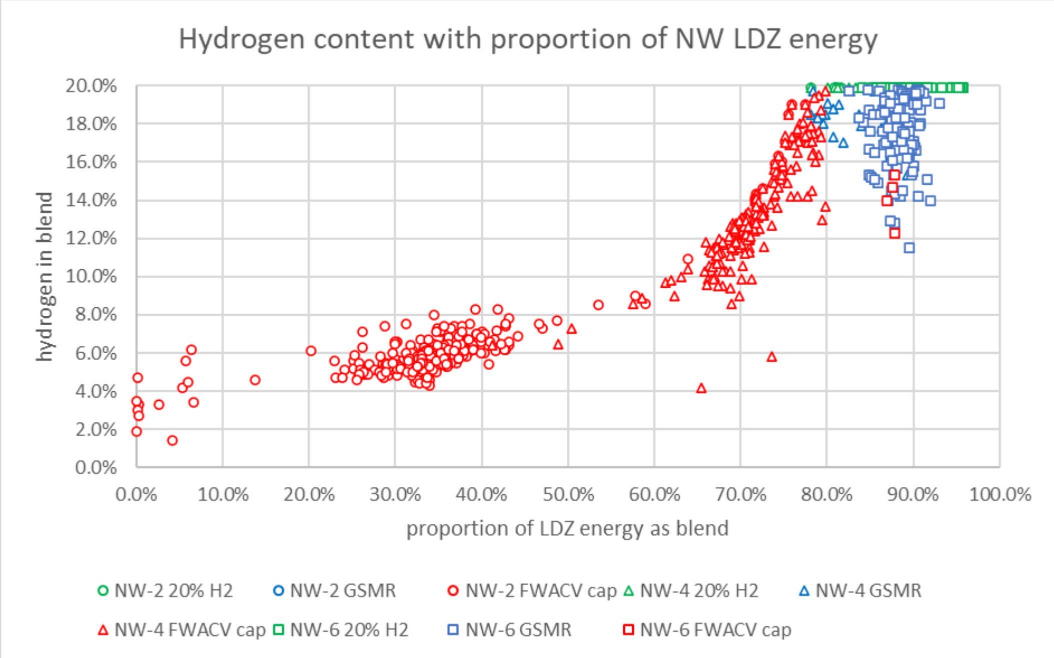


Figure 10: Principal cause of constraint in proportion of hydrogen in blend in NW LDZ.

Key: Green – 20% H2; Blue – GSMR; Red – FWACV cap [Summary_NW-EM_sort]

Table 1 below shows the number of days within 2020 that could accommodate a given range in hydrogen content for the three cases (injection at 2, 4 and 6 NTS offtakes).

Table 1: Number of days for which a given proportion of hydrogen in blend could have been accommodated in NW LDZ.

%H2	GSMR lower limit 47.2 MJ/m^3			GSMR lower limit 46.5 MJ/m^3		
	NW-2	NW-4	NW-6	NW-2	NW-4	NW-6
0-2%	40	3	3	40	3	3
2-4%	6	0	0	6	0	0
4-6%	178	2	0	178	2	0
6-8%	111	3	0	111	3	0
8-10%	6	16	0	6	16	0
10-12%	1	53	1	1	52	0
12-14%	1	82	3	1	80	1
14-16%	5	42	22	5	26	3
16-18%	7	60	44	7	29	2
18-20%	10	104	292	10	154	356
total	365	365	365	365	365	365

7 HYDROGEN INJECTION IN EM LDZ

7.1 ESTIMATE OF CONSTRAINTS ON THE DAILY AMOUNT OF HYDROGEN THAT CAN BE ADDED

7.1.1 INPUT POINTS TO EM LDZ

A total of 22 input points to the EM LDZ were assumed in the LDZ model for EM LDZ:

- Nine NTS offtakes at Alrewas, Blaby, Blyborough, Caldecott, Drointon, Gosberton, Market Harborough, Thornton Curtis and Tur Langton
- Four "tracker-only" sites at Kirkstead, Silk Willoughby, Sutton Bridge, and Walesby

- Nine biomethane injection sites at Bonby, Hemswell, Hibaldstow, Lindholme, Manor Farm, Metheringham, Scampton, Stoke Bardolph and Welbeck

For the Tracker-only sites, the EOD file contains data arising from use of an inferential device (based on the GasPT). For the purposes of the calculation of FWACV, the daily average CV for each site is not the value measured at site, but that attributed from a nearby site. In the case of Kirkstead and Sutton Bridge, the daily average CV is mapped to that at Gosberton NTS offtake. In the case of Silk Willoughby and Walesby, the daily average CV is mapped to that at Hatton Multi-junction site.

Because the tracker-only sites are small – together they supply around 1.18% of total LDZ energy – the daily average CV of all tracker-only sites was mapped to that Gosberton for this study because data transfer problems prevented acquisition of data for Hatton multi-junction.

The biomethane sites are "Directed Sites"[5] employing an Ofgem-approved CV determination device, so daily average CV, RD, volume, energy were available from the EOD files. Because un-enriched biomethane would become the LSCV on all gas days, it is generally enriched with commercial propane so as to ensure that the FWACV cap does not occur. For this study, addition of hydrogen whilst simultaneously "un-enriching" the biomethane is a complex operation and so for this study the daily average CV at the biomethane sites was ignored in determination of the LSCV.

This is a reasonable assumption because the sites are small – contributing a total of 0.95% of total LDZ energy – and after addition of hydrogen the blend would be the LSCV and not the CV of unenriched biomethane.

7.2 ADDITION AT 1 OFFTAKE ONLY

Figure 11 shows the plot of proportion of hydrogen that could have been added on each gas day against the proportion of EM LDZ energy that is blend for the case in which blend is supplied through one EM offtake only.

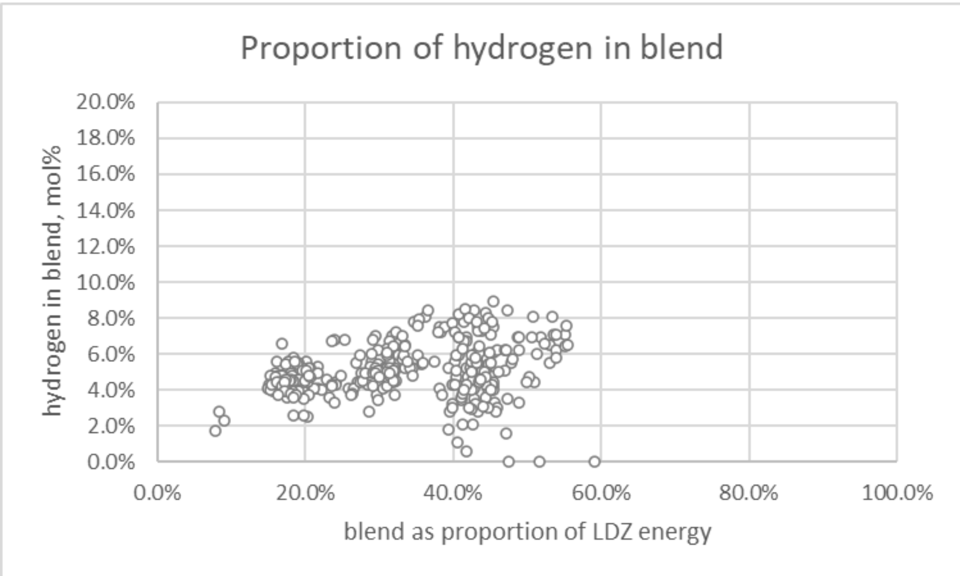


Figure 11: Proportion of hydrogen that can be added at one EM NTS offtake against proportion of EM LDZ energy flowing as blend. [LDZmodel42-1]

[5] Directed sites are those for which Ofgem have directed the gas transporter to determine CV pursuant to Regulations 6 (a) and 6 (b) of the GCOTER.

7.3 ADDITION AT TWO NTS OFFTAKES

Figure 12 shows the plot of proportion of hydrogen that could have been added at 2 offtakes on each gas day against the proportion of EM LDZ energy that is blend.

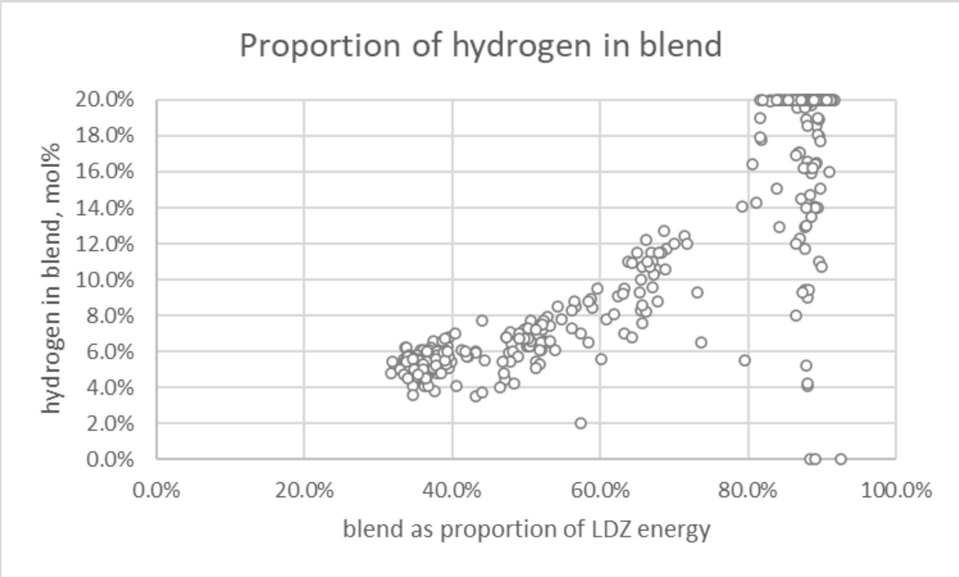


Figure 12: Proportion of hydrogen that can be added at 2NTS offtakes against proportion of EM LDZ energy flowing as blend. [LDZmodel42-2]

7.4 ADDITION AT FOUR NTS OFFTAKES

Figure 13 shows the plot of proportion of hydrogen that could have been added at four NTS offtakes on each gas day against the proportion of EM LDZ energy that is blend.

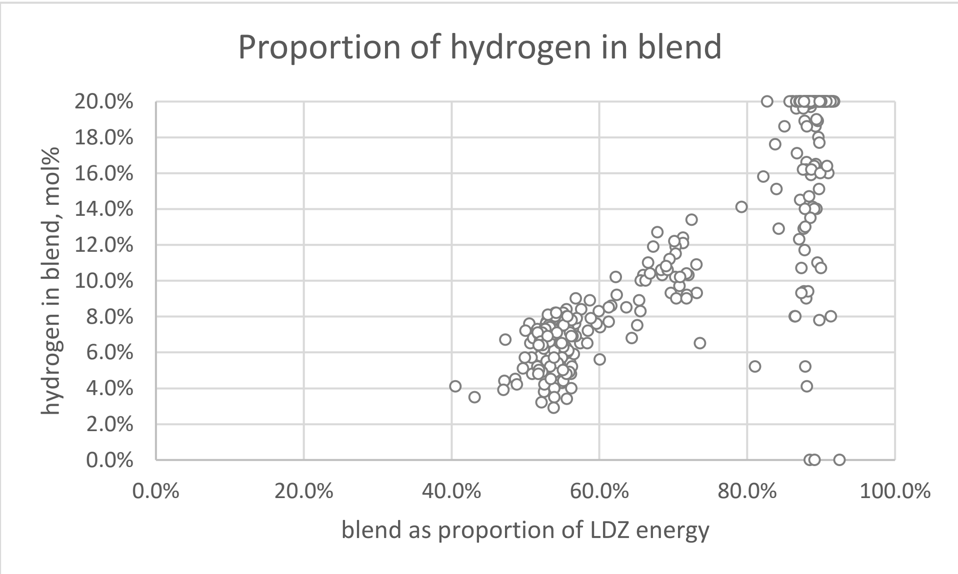


Figure 13: Proportion of hydrogen that can be added at four NTS offtakes against proportion of EM LDZ energy flowing as blend. [LDZmodel42-4_6431]

7.5 ADDITION AT SIX NTS OFFTAKES

Figure 14 shows the plot of proportion of hydrogen that could have been added at six NTS offtakes on each gas day against the proportion of EM LDZ energy that is blend.

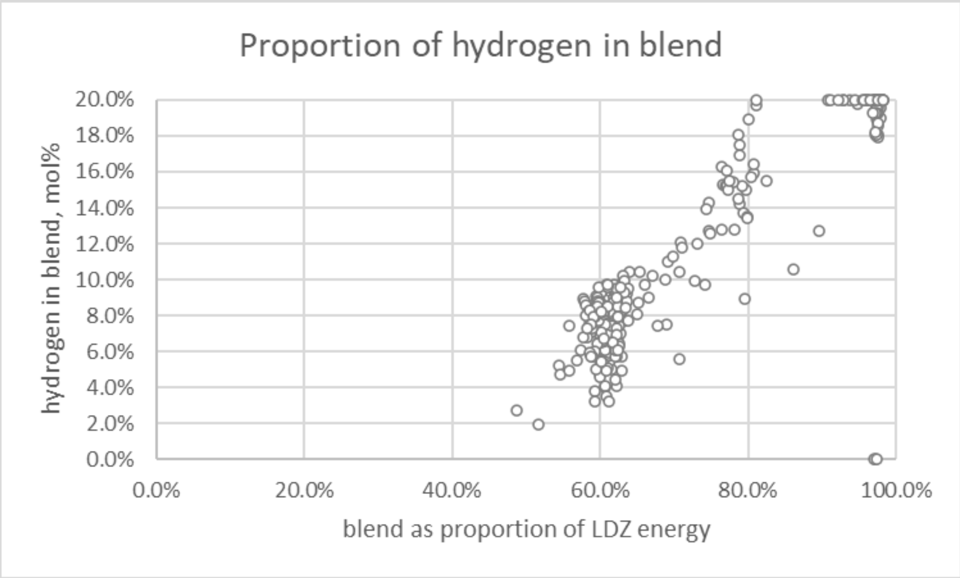


Figure 14: Proportion of hydrogen that can be added at six NTS offtake against proportion of EM LDZ energy flowing as blend. [LDZmodel42-6]

Figure 15 is a composite plot of the proportion of hydrogen in the blend as the proportion of LDZ energy supplied as blend increases. The data is for injection into EM LDZ at 2, 4 and 6 NTS offtakes.

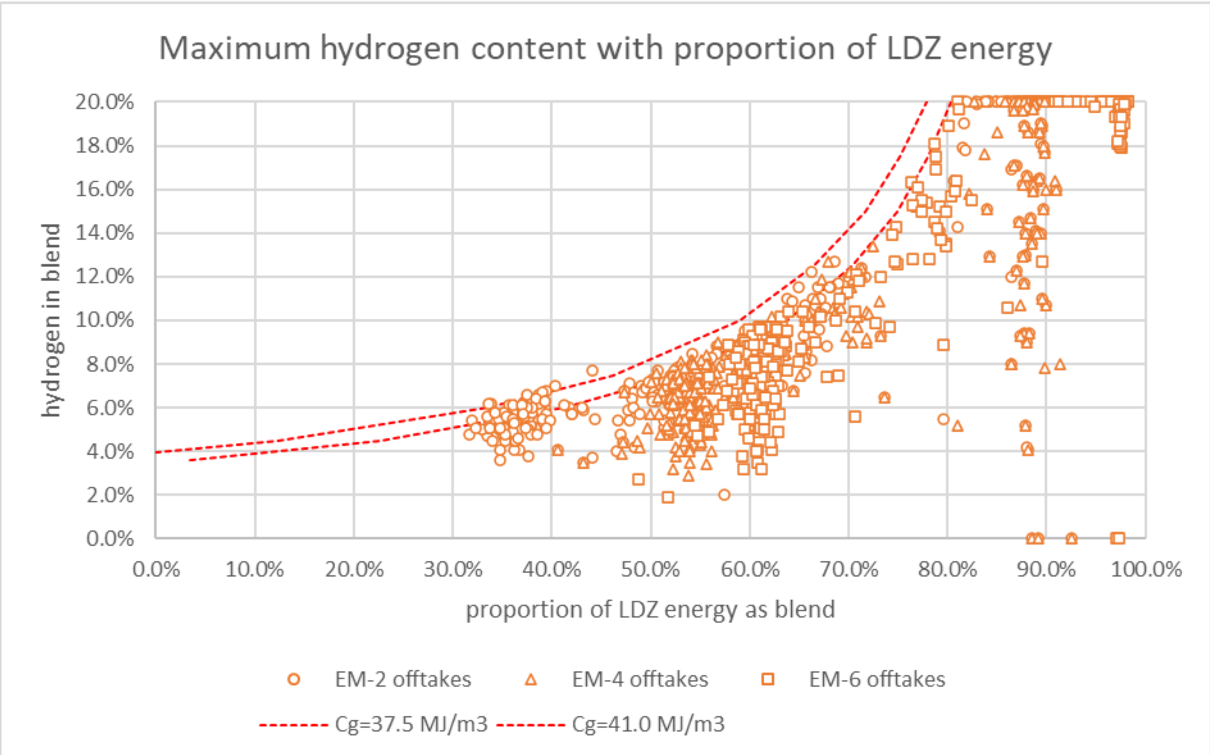


Figure 15: Composite plot of injection of hydrogen into EM LDZ at 2, 4 and 6 NTS offtakes [Summary_NW-EM_sort]

Figure 16 is a composite plot of the change in FWACV as the proportion of LDZ energy supplied as blend increases. The data is for injection into EM LDZ at 2, 4 and 6 NTS offtakes.

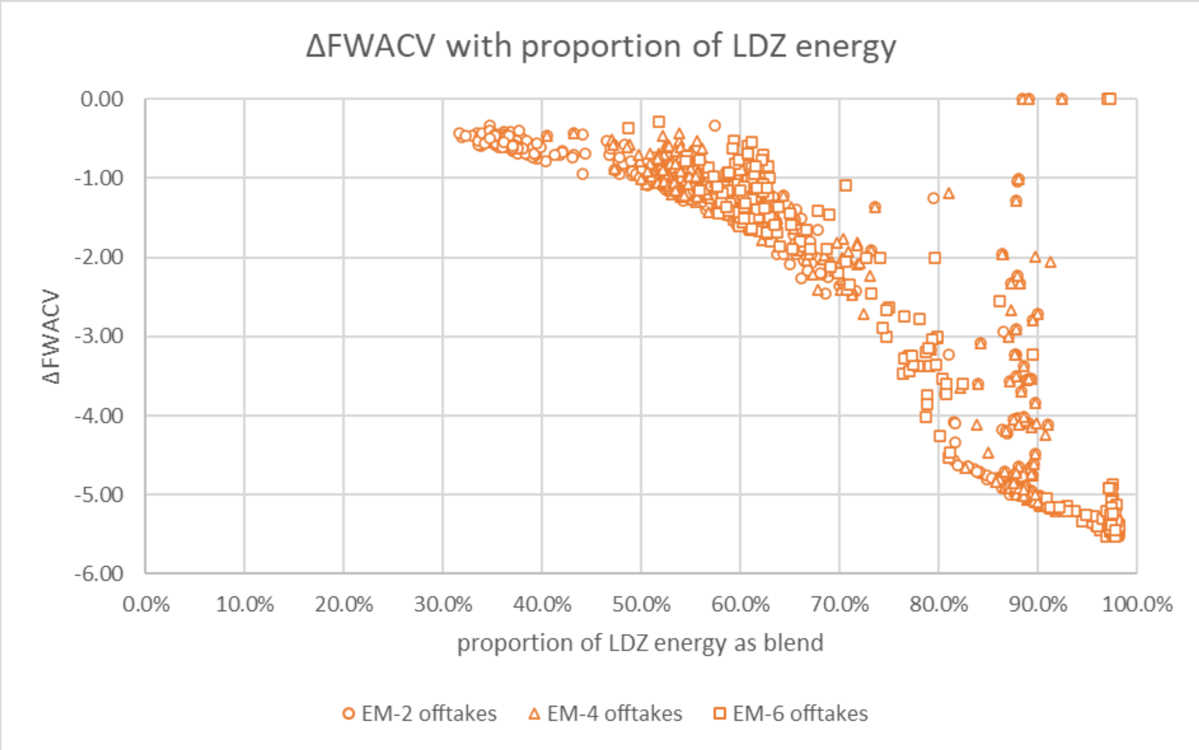


Figure 16: Composite plot of change in FWACV as the proportion of LDZ energy as blend increases [Summary_NW-EM_sort]

7.6 PRINCIPLE CAUSE OF CONSTRAINT IN ADDITION OF HYDROGEN – EM LDZ

The principal cause of constraint in the proportion of hydrogen that can be added are illustrated in Figure 17, which shows the data for three scenarios of addition (injection at 2, 4 and 6 NTS offtakes). Data points are colour coded by principle cause: red points correspond to FWACV capping, blue points correspond to the lower WI index of the existing GSMR, and green points correspond to the proposed 20% hydrogen limit.

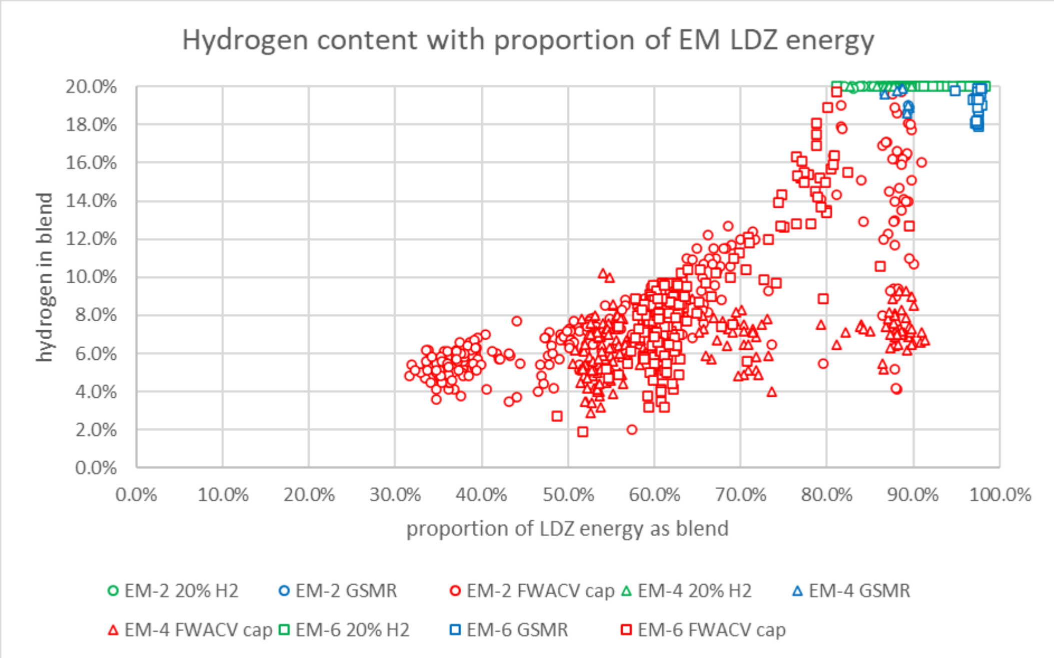


Figure 17: Principal cause of constraint in proportion of hydrogen in blend in EM LDZ

Key: Green – 20% H2; Blue – GSMR; Red – FWACV cap [Summary_NW-EM_sort]

Table 2 below shows the number of days within 2020 that could accommodate a given range in hydrogen content for the three cases (injection at 2, 4 and 6 NTS offtakes).

Table 2: Number of days for which a given proportion of hydrogen in blend could have been accommodated in EM LDZ.

%H2	GSMR lower limit 47.2 MJ/m^3				GSMR lower limit 46.5 MJ/m^3			
	EM-1	EM-2	EM-4	EM-6	EM-1	EM-2	EM-4	EM-6
0-2%	8	3	3	4	8	3	3	4
2-4%	50	5	7	5	50	5	7	5
4-6%	227	112	61	32	227	112	61	32
6-8%	68	74	110	64	68	74	110	64
8-10%	12	24	33	80	12	24	33	80
10-12%	0	18	23	10	0	18	23	10
12-14%	0	11	10	11	0	11	10	11
14-16%	0	11	11	14	0	11	11	14
16-18%	0	14	12	6	0	14	12	6
18-20%	0	93	95	139	0	93	95	139
total	365	365	365	365	365	365	365	365

8 COMPARISON OF NW LDZ AND EM LDZ

Comparison of the composite plots in Figures 10 and 17 shows the following:

a) Overall behaviour is similar, i.e., increasing the proportion of LDZ energy allows a higher proportion of hydrogen in the blend without triggering a FWACV cap. A proportion of LDZ energy supplied as blend of 80% or more is generally required to achieve 20% hydrogen.

b) In general, FWACV capping constrains hydrogen addition to lower proportions to a greater extent when injecting into EM LDZ than when injecting into NW LDZ. The reason for this is that there is a greater variation in CV in EM LDZ than in NW LDZ. When there is little variation in CV of natural gas within an LDZ the idealised behaviour given by Equation (1) dominates.

However, if there is a wider spread in CV across the LDZ then the extent to which FWACV is reduced as hydrogen is injected is diminished by presence of high CV gas. When there is a range of CV in an LDZ, FWACV capping provides more of a constraint if hydrogen is added to the lower CV natural gas than if it were added to high CV gas.

c) When blend supplies around 80% of LDZ energy, although FWACV capping does not typically restrict hydrogen content, the lower WI limit of the GSMR may constrain hydrogen content to less than 20%. The blue data points in Figures 10 and 17 show that GSMR constraints would have been more frequent for injection into NW LDZ than for injection into EM LDZ. This is because in general the WI of natural gas in NW LDZ was lower than in EM LDZ and so less hydrogen can be accommodated.

d) Lowering the WI lower limit of the GSMR would reduce the constraint seen when blend is at a high proportion of LDZ energy and is most evident for hydrogen injection into NW LDZ. This can be seen in Figure 18, which is a plot for injection into NW LDZ at 4 NTS offtakes with the GSMR lower WI limit reduced from 47.2 MJ/m^3 to 46.5 MJ/m^3. Comparison with Figure 8 shows a lower incidence of proportions of hydrogen lower than 20% when proportion of LDZ energy as blend is at or above 80%.

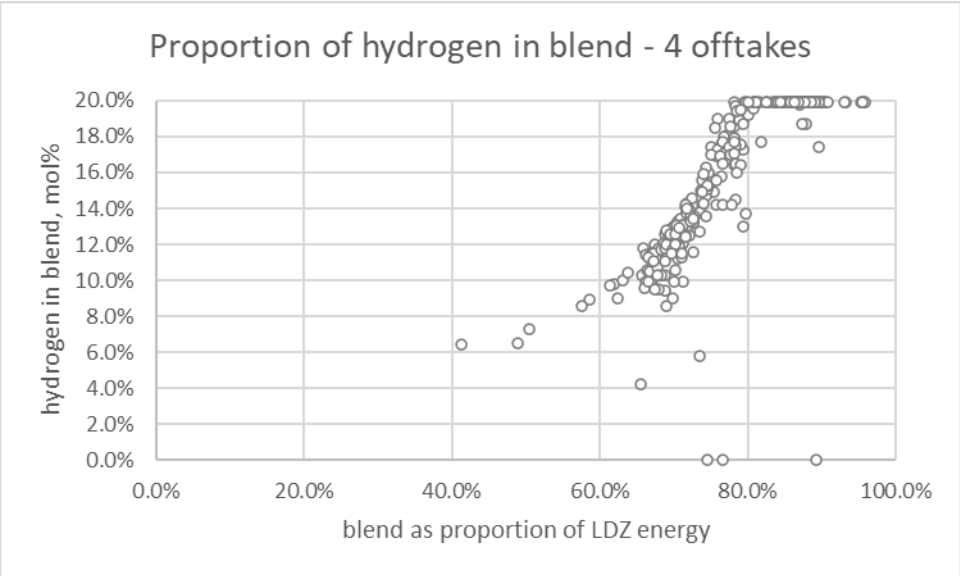


Figure 18: Plot of proportion of hydrogen in blend as the proportion of NW LDZ energy as blend increase for the case of injection at four NTS offtakes. Note that lower WI limit of the GSMR was reduced to 46.5 MJ/m^3 [LDZmodel42-4_6431_46.5]

Tables 1 and 2 show the number of days within 2020 that could accommodate a given range in hydrogen content for each case studied for the situation in which the WI lower limit in the GSMR is either 47.2 MJ/m^3 or lowered to 46.5 MJ/m^3. A reduced WI lower limit would have enabled 18-20% hydrogen to be injected for more days for injection into the NW LDZ. For injection into EM LDZ a reduced WI lower limit makes no difference because the existing GSMR constraints are not large (see Figure 17 – the blue data points are all for hydrogen proportions of 18% or more).

9 IMPACT OF HYDROGEN INJECTION ON INJECTION OF BIOMETHANE

The CV of un-enriched biomethanes is typically around 36.1 – 37.4 MJ/m3 and so cannot be injected into LDZs without management of FWACV capping. FWACV capping can be avoided by blending biomethane with natural gas, either passively, by simple comingling with gas that flows past the injection point, or actively at a dedicated blending facility such as SGN's facility at Portsdown Hill. However, capping is most often avoided by enrichment with commercial propane.

Gas Distribution Networks generally set a target CV for biomethane producers and require CV of enriched biomethane to remain at or above the target CV. The target CV value is based on the expected FWACV with a suitable safety margin. Because hydrogen injection at NTS offtakes will reduce FWACV, it is likely that the need for enrichment will be reduced, or possibly eliminated, in periods when hydrogen injection is carried out.

Figure 19 shows two composite plots of the daily LSCV in 2020 that would have arisen when injecting hydrogen into both NW LDZ and EM LDZ. Also shown in Figure 19 is the typical range in CV of unenriched biomethanes. From Figure 19 it can be seen that:

- When blend supplies between 0% and ca. 30% of LDZ energy, all unenriched biomethanes are likely to remain the LSCV and so some degree of enrichment would be required.
- When blend supplies more than ca. 75% of LDZ energy, all unenriched biomethanes would have a higher CV than the LSCV and so for much of the time, no enrichment would be required. Note that at some time, FWACV capping would still prevent sufficient hydrogen to be injected to remove the need for enrichment of some biomethanes.
- When blend supplies between ca. 30% and ca. 75% of LDZ energy, some biomethanes would need either less or no enrichment.

It is likely therefore that enrichment of biomethane could be minimised or eliminated for periods when significant hydrogen injection is practiced. This will reduce operating costs for biomethane production (principally cost of propane). However, it is likely that some enrichment may still be required for some periods of time, so capital costs for enrichment facilities are likely to still be needed with future biomethane projects.

A similar argument can be proposed for blending of biomethane: the reduction in FWACV will reduce the required minimum CV of biomethane-natural gas blend and hence more biomethane can be accommodated for a given level of demand downstream of the injection point.

Typically, unenriched biomethanes produced in recent biomethane injection projects contain relatively small amounts of inerts and are compliant with the lower WI limit of the GSMR[6]. In such a situation injection of biomethane into a hydrogen-natural gas blend that is compliant with the lower WI limit of the GSMR would not result in a non-compliant gas.

[6] This is thought to be because the growth in biomethane injection projects has led to better control of AD plant conditions so as to minimise inerts content of raw biogas and hence minimise biomethane enrichment costs.

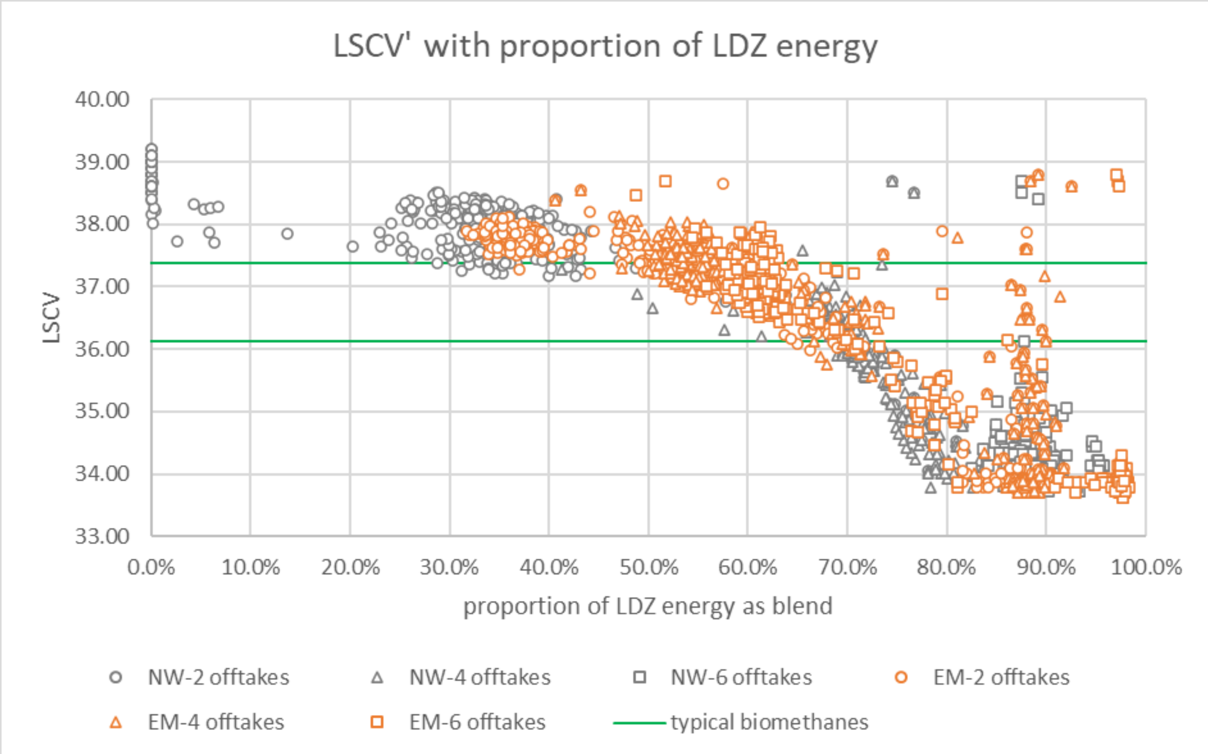


Figure 19: Composite plot of LSCV for hydrogen injection into NW LDZ and EM LDZ. Key: grey points – NW LDZ; orange points – EM LDZ; green lines – range in CV of typical unenriched biomethanes. [Summary_NW-EM_sort]

10 METERING IMPACTS

An indicative expected impact of hydrogen on existing metering facilities has been assessed using a NW NTS offtake as an example. The metering facility at the offtake is an orifice plate system and flowrate was calculated using the following data and assumptions:

- Pipe and orifice diameters from Cadent
- Isentropic upstream temperature correction
- Pressure and temperature assumed to be 60 barg and 10°C
- Isentropic index calculated from the AGA10 equation
- Density calculated from the AGA8 (Detailed Composition) equation
- Expansibility and pressure loss according to ISO 5167:1991/97
- Upstream viscosity from LBC equation
- Flange taps, discharge coefficient from MRH equation

Note that the last three items assume that the relevant equations/correlations apply to a 20% hydrogen – natural gas mixture.

The approach taken was to evaluate at the average and maximum flowrates seen at the offtake and calculate the differential pressure across the orifice plate when natural gas and when a 20% hydrogen blend was flowing. The results are shown in Table 3.

Table 3: Orifice plate metering assessment for the offtake

	Flowrate (2020), m3/d	DP (natural gas), mbar	DP (20% hydrogen, same daily energy)
Average	94,076 (6.72% Qmax)	2.232	2.684 mbar (+20.25%)
Maximum	4,049,899 (28.9% Qmax)	41.53	49.94 mbar (+20.25%)

From Table 3 it can be seen that:

- The offtake was operating well below its maximum design flowrate during 2020
- When metering a 20% blend, differential pressure would increase by around 20% for the same energy flowrate. The capacity of the metering system would therefore be reduced by approximately 20%

Cadent have a programme of upgrading metering facilities at their NTS offtakes to use ultrasonic meters and so their suitability for metering blends should be established. Sick have issued a White Paper[7] on their evaluation of suitability of their USMs for metering of hydrogen – natural gas blends and have concluded:

> *Gas flow meters of the SICK FLOWSIC600 and FLOWSIC600-XT families, due to their ultrasonic technology, are already suitable today for measuring natural gases containing proportions of hydrogen up to 10% by volume within the scope transport according to the laws of calibration. The reliability and quality of the measurement results are not affected by changes in density, flow velocity or speed of sound.*
>
> *SICK will continue to investigate the measuring capability of ultrasonic gas meters for hydrogen-containing natural gas, especially with proportions of 25% by volume (and above), and if necessary, will adapt the measuring devices to meet the market requirements for precise gas flow rate measurement which are capable of calibration requirements.*

It is likely therefore that upgrading to USMs will not compromise metering accuracy with blend, although design and selection of system should allow for the possibility of the need to convey up to 20% hydrogen.

11 NETWORK CONTROL

11.1 OPTIMISING NETWORK FOR HYDROGEN BLENDING

As discussed above, the NW NTS offtake was operating a well below design capacity during 2020 and so in general hydrogen injection can be optimised by maximising flow through NTS offtakes where hydrogen is being injected.

The maximum quantity of hydrogen that could be injected in NW LDZ and in EM LDZ was estimated if flow through offtakes were maximised. Maximum flows through the chosen flowrates and the proportion of LDZ energy was modelled by Cadent. The mole fraction of hydrogen for a given proportion of LDZ energy was estimated from the average hydrogen mole fraction suggested by the appropriate LDZ model. From the NTS offtake flows and hydrogen mole fraction the daily and annual quantities of hydrogen injected were calculated. These can then be compared with the (un-optimised) results.

Table 4 summarises the optimised flows for three scenarios:

- Hydrogen injected 2 offtakes in NW LDZ
- Hydrogen injected at 1 offtake in EM LDZ
- Hydrogen injected at 3 offtakes in in EM LDZ

[7] SICK AG White Paper. FLOWSIC600 / FLOWSIC600-XT POWER-TO-GAS – Admixture of hydrogen from renewable energies into the natural gas grid and the associated suitability of SICK ultrasonic gas meters. (November 2019)

Table 4: Comparison of un-optimised with potential optimised hydrogen injection in NW and EM LDZs

Scenario	Hydrogen injected	Un-optimised	Optimised
– Hydrogen injected 2 offtakes in NW LDZ	Average mole fraction	5.9%	14.5
	Quantity, million m^3/y	140.3	574.0
	Quantity, TJ/y	1698	6946
– Hydrogen injected at 1 offtake in EM LDZ	Average mole fraction	5.0	6.1
	Quantity, million m^3/y	73.3	149.6
	Quantity, TJ/y	886	1810
Hydrogen injected at 3 offtakes in in EM LDZ	Average mole fraction	-	17.5
	Quantity, million m^3/y	-	894
	Quantity, TJ/y	-	10820

The results suggest that hydrogen injection in NW LDZ at 2 offtakes could be increased by a factor of around 4 by optimising NTS offtake flows. Hydrogen injection in EM LDZ at 1 offtake could be increased by a factor of around 2 by optimising NTS offtake flows.

11.2 IMPLICATIONS OF OPTIMISING NETWORKS FOR HYDROGEN INJECTION

Management of FWACV capping, GSMR compliance and setting and communication of target CV to biomethane producers are all interlinked to hydrogen blending and in turn to the availability and shipper nomination of hydrogen supplies into the LDZ. This adds an additional layer of complexity to current network operations. As a consequence, Gas transporters may need to assume a greater degree of day-to-day and within-day control over when, where and how much hydrogen injection is practiced. In turn this may require Gas transporters to exercise control/advice over where natural gas supplies enter the NTS and LTS order to manage networks effectively.

In addition, GDNs are likely to need improved tools for network control so as to enable efficient handling of regulatory constraints, interactions between hydrogen injection points and CV target setting for biomethane producers.

12 HYDROGEN INJECTION INTO LOWER PRESSURE TIERS

The billing impact of hydrogen injection (i.e., the potential for capping of the daily FWACV) occur wherever hydrogen is injected into the LDZ. However, injection into lower pressure tiers has implications for the scale and number of hydrogen injection projects that would be required. This study demonstrates that significant hydrogen injection without FWACV capping requires blend to be a significant proportion of LDZ energy. Achieving a significant flow of blend requires there to be significant demand downstream of the injection point and whilst there is significant demand at the NTS offtake, within the lower pressure tiers demand at any given point declines significantly.

For instance, for a typical pressure reduction installation controlling entry of gas into a 7 bar system annual average flowrate may be ca. 30,000 m^3/h. For a typical natural gas (GCV 38.5 – 40 MJ/m^3) a maximum of around 3.68% hydrogen can be accommodated before GCV is lowered by 1 MJ/m^3 and hence is likely to trigger a cap in FWACV. The average flowrate of hydrogen that could be accommodated at such a location would be just 1105 m^3/h. To match the un-optimised hydrogen flowrate of 73.3 million m^3/y (8368 m^3/h) at the offtake would therefore require injection at 8 sites. For the optimised hydrogen flowrate at the offtake, around 15 sites would be required.

For injection into the MP system, typical annual average demand at biomethane sites is around 1000 m^3/h and hence matching the un-optimized and optimised offtake flowrates would require 227 and 464 sites, respectively.

Injection at the NTS offtake therefore offers the most efficient route – in terms of numbers of sites – for rapid expansion of hydrogen injection capacity for Gas Distribution Networks.

13 MISCELLANEOUS OBSERVATIONS

During the study, a number of observations have been noted that will need to be addressed in order to progress hydrogen injection at NTS offtakes:

- The DANINT/EODAVE software employed at Directed Sites uses a value of 35 MJ/m^3 for daily average CV as a flag for zero CV records in day. CVs equal to or lower than this are possible with blends and so the software (and the MARQUIS information system, which receives the EOD files from site) will need amendment to employ an alternative flag. The EODAVE module within DANINT is approved by Ofgem and so any modifications will require its re-approval.
- Hydrogen analysis is a pre-requisite for both metering purposes and CV determination. A new or modified CV determination device will need to be employed and this will require approval from Ofgem.
- CVDD determination at tracker-only sites (for determination of daily energies) currently employs inferential devices that currently are not suitable for hydrogen blends. However, it is unlikely that hydrogen would be injected at such sites because of their low capacity. Injection of hydrogen into the NTS could render them unsuitable, however.

14 NUMERICAL DATA

Tabulations of numerical data from the assessment are supplied in a separate spreadsheet.

15 CONCLUSIONS

a) Hydrogen injection at the NTS offtake offers a means of achieving conveyance of a natural gas blend containing up to 20% hydrogen within the existing regulatory framework of the GCOTER and within the GSMR, providing the existing maximum limit on hydrogen content can be modified to allow conveyance from 0.1% to up to 20% hydrogen.

b) Capping of FWACV is the principal constraint on the proportion of hydrogen than can be accommodated. The proportion of hydrogen that can be blended varies from around 4% when a relatively small proportion of LDZ energy is supplied as blend, to up to 20% when around 80% or more of LDZ energy is supplied as blend. As a general rule therefore, blend should dominate the amount of energy supplied to a given LDZ. This can be achieved through supplying blend through multiple offtakes or though one large offtake.

c) Adding a significant proportion of LDZ energy as blend reduces the FWACV and hence reduces risk of capping.

d) FWACV capping is more of a constraint if the CV of natural gas supplies into an LDZ vary significantly. In such situations, the reduction of FWACV is not so great particularly if hydrogen is blended with lower CV supplies. This is seen with EM LDZ, where the range of CV is greater than with NW LDZ. As a general rule hydrogen injection is more effective if added to the highest CV source.

e) The lower Wobbe index (WI) limit of the GSMR can constrain the proportion of hydrogen that can be injected to less than 20%, even if blend is supplying in excess of 80% of LDZ demand. Such GSMR constraints occur if the WI of the natural gas in the LDZ is closer to the GSMR lower limit and occurs more frequently with NW LDZ than with EM LDZ. A future proposed reduction in the lower WI limit in the GSMR would reduce the incidence of this constraint in the NW LDZ.

f) Because hydrogen injection at the NTS offtakes reduces the FWACV, the enrichment requirements for existing and future biomethane injection projects are likely to be reduced. However, it is unlikely that the need for enrichment would be removed completely, so although operating cost can be reduced, the capital investment for enrichment plant for future projects is unlikely to be avoided.

g) In principle, existing metering systems at the NTS offtakes are not likely to be compromised by injection of hydrogen, although upgrade of equipment will be required. Future plans for upgrading such sites will need to be designed to accommodate hydrogen injection.

h) Hydrogen injection adds an additional layer of complexity to network control and operation and better tools are likely to be required. The gas transporter will need to exercise more control over balancing of when, where and how much hydrogen is injected against FWACV and GSMR constraints. This will need significant discussion and agreement within the industry.

APPENDIX A: GLOSSARY OF TERMS

CV	-	Calorific Value
CVDD	-	Calorific value determination device
Directed Sites	-	Sites for which Ofgem have directed the gas transporter to determine CV pursuant to Regulations 6 (a) and 6 (b) of the GCOTER
FWACV	-	Flow Weighted Average Calorific Value
GCOTER	-	The Gas (Calculation of Thermal Energy) Regulations
GCV	-	Gross Calorific Value
GSMR	-	The Gas Safety (Management) Regulations
LDZ	-	Local Distribution Zone
LSCV	-	Lowest Source Calorific Value
WI	-	(Gross) Wobbe index