Capacity issues on converting natural gas network to supply hydrogen

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Abstract

It is expected that the existing natural gas network can be converted to carry hydrogen using the new polyethylene pipes installed through the UK's ongoing Iron Mains Replacement Programme.

The energy density of hydrogen is considerably lower than natural gas. This means that in order to deliver the same energy to consumers as at present, the volume flow rate must be considerably greater. As a corollary, the flow velocity will also be considerably higher.

Here we explore the questions of whether existing networks can have sufficient capacity to deliver enough hydrogen to consumers, within existing flow and velocity constraints.

We built a Python model of a hypothetical natural gas network, kept deliberately low in excess capacity. The model was then tested with hydrogen. This allowed the investigation of the effects on a range of pipe sizes, under differing pressure, flow and demand conditions.

We found that in most modelled situations sufficient hydrogen could be transported. The lower density and viscosity of hydrogen mean that the pressure loss is less than might have been expected from the higher flow velocities, although there is still invariably a bigger pressure loss than for natural gas. There are situations where the velocity and pressure tolerances are exceeded at peak times.

In these cases, additional short term downstream storage, not exceeding 24 hours' supply, and/or boosting the upstream pressure are required to restore service.

A means of predicting where constraints will be exceeded is also tentatively proposed.

1 Introduction

It has been described, or accepted [5], that the natural gas network in the UK could, in principle, be converted to carry hydrogen. This is because the polyethylene pipes which comprise the majority of the natural gas network are thought to be safe for the transportation of hydrogen [6, 7]. These polyethylene pipes have been installed as part of the UK mandated Iron Mains Replacement Programme, which is a replacement of all the UK's iron gas mains within 30 metres of a property for safety reasons, over a 30 year period scheduled to finish in 2032 [1].

Hydrogen is a potential replacement for natural gas. It may be possible in principle to convey hydrogen through the existing and anticipated polyethylene pipes, however the question remains as to whether the network will have sufficient capacity to deliver enough hydrogen to consumers. This is very important to understand in planning the re-use of existing natural gas networks to transport hydrogen to consumers.

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While the specific energy of hydrogen is about 2.6x higher than natural gas, the energy density of natural gas is about 9 – 11x greater than hydrogen (pressure dependent) [18]. This means that in order to deliver the same amount of energy to consumers as is currently delivered using natural gas, the volume flow rate of hydrogen must be approximately 3-4 times greater.

This increased volume flow, and hence flow velocity, can be expected to increase the pressure drop within a pipe if it delivers the same amount of energy. Conversely, the lower viscosity and density of hydrogen can be expected to offset this effect - the net effect of the combination of these factors will be explored in the course of this research, although from previous works it appears that there will be a net reduction in maximum carrying capacity [7] [8]. This is complicated by the fact that gases are compressible, so the viscosity and density of a gas change with pressure.

The key physical characteristics of the pipe determining the pressure drop are length, diameter, internal surface roughness, and overall change in elevation. The pipe and fluid characteristics, and the flow velocity, control the pressure drop.

The allowable flow in a pipe is constrained by two external factors: (1) the network operational requirements dictate the maximum allowable pressure drop within a pipe length; (2) network operators work to an maximum permissible flow velocity, to limit the amount of scour that might occur on the inside of pipes due to the entrainment of dust in the gas flow [4].

The existing pipe network is therefore constructed with big enough diameter pipes to supply enough natural gas to meet users' energy demands. The key question we address here, then, is: can the same pipes deliver enough hydrogen to meet the same energy demands?

Fundamental to this question is how much 'spare' capacity is there in each pipe? It is unlikely that many pipes will be sized such that the demand is equal to the maximum capacity of the pipe. If the pipe maximum capacity at present were below the demand level, then clearly the demand could not be met – the effect of this would be that appliances at the downstream end of the network would not receive enough gas to function effectively and safely. Connected with this, commercially made pipes are available in a range of fixed sizes, rather than being made to suit specific applications. On the other hand, if an existing pipe has a large amount of excess capacity at present, then it will be much more likely to have enough extra capacity to deliver hydrogen. A way of estimating or assuming the excess capacity currently available with natural gas will be required.

To investigate these questions, we constructed and interrogated a hypothetical model using Python. We express two hypotheses investigated in this way:

1. A natural gas network can be converted to supply enough pure hydrogen to replace all natural gas in use, on the basis of energy transported, without enlargement or replacement of the pipes.
2. It will be possible to identify which parts of the network are likely to need intervention when converted to supply hydrogen, on the basis of the natural gas characteristics alone.

The extent to which finding will apply only to the UK or to a broader global situation will also be discussed.

To ensure that the model is at a realistic scale, it was inspired by the existing network for natural gas serving the east of Scotland. This starts from the main injection point at St. Fergus, on the east coast, north of Aberdeen, down to the Scottish Borders region in the south. It's important to emphasise that this is not intended to be a representative model of that network; that network has just been used to make sure that this hypothetical model is at an appropriate scale.

The UK gas operating companies have a range of operating pressures at which they operates the gas means. There are four different classes of pressure ratings for gas pipes [3]:

High Pressure / Transmission mains 700 – 8500 kPa
Intermediate pressure 200 – 700 kPa
Medium pressure 7.5 – 200 kPa
Low pressure / distribution mains – below 7.5 kPa. These are the pipes which deliver gas into consumer's property.

For the purposes of this analysis, only high and intermediate pressure pipes were considered. The model, described in more detail below, takes the core transmission network as equivalent to high pressure. The pipes leading to the demand nodes are taken as equivalent to intermediate pressure pipes. These two classes of pipe are termed 'network pipes' and 'demand pipes' in the model respectively. The implication is that the medium and low pressure mains comprise the distribution network downstream of the modelled demand points. In the real network, however, the application of the different pressure regimes is not so clear cut, but for the purposes of this analysis we consider the simplification to be valid.

The maximum allowable flow velocity for natural gas is 40 m/s, although it is common for network operators to limit velocities to 20 m/s as much as possible [4]. It is possible that a higher velocity might be acceptable if it can be shown that the dust transported by hydrogen is lower than that transported by natural gas at higher flow velocities. That is outwith the scope of this analysis, however, although the extent to which the high velocity problem exists will be identified.

1.1 **Previous Relevant Work**

In *An Investigation into the Volumetric Flow Rate Requirement of Hydrogen Transportation in Existing Natural Gas Pipelines and Its Safety Implications*, Abbas et al [8] limit their analysis to a single large diameter pipe. They mention a 3x increase in volume flow requirement, though this refers to the volume difference at ambient conditions rather than at pressure.

In *Conversion of the UK gas system to transport hydrogen*, Dodds & Demoulin [7] carry out a series of expert interviews and a literature review to consider broadly the opportunity to convert the UK gas network to supply hydrogen. In terms of energy transportation capacity, they find that the energy transmissibility with hydrogen is 'approximately 20% lower' than for natural gas, in the same pipe and upstream pressure.

Dodds & Demoulin also anticipate an increase of 25% (which could be mitigated) in demand for gas-transported energy, with the expectation that households would adopt fuel cell powered micro-CHP (Combined Heat & Power generation) instead of the conventional heating boilers. This is in contrast to the current trend towards electric powered heat pumps for domestic heating [9]. A number of studies have considered a combined approach between these two technologies, for example Yang et al [10] and Cooper et al [11].

In this study, the related aim is to develop from this work and consider a wider range of pipe diameters and pressure regimes, to understand if the 3x factor in Abbas et al [8] is broadly applicable, to confirm the 'approximately 20%' reduction in energy transmissibility in Dodds & Demoulin [7], and to understand the relevance of those figures in a more detailed scenario.

2 Methods

2.1 Network Arrangement

The hypothetical model was created with a 'tree' type network, that is a central core, or trunk, with branches but no loops. This is considerably easier to model than a looped network, and will still provide valuable data outputs. The key network nodes were taken at key points of the real network used as a basis, and the demand nodes were based on local authorities. This was because enough information is collected at the level of local authorities to allow these to be created as realistic demand points.

A single injection node was created in the north-east, equivalent to the injection point for all of the natural gas currently used in Scotland and about one-third of the UK overall [19]. A related assumption is that the hydrogen would be produced offshore at the anticipated extensive North Sea wind farms [12], or immediately onshore with electricity direct from those windfarms, and similarly injected into the network in the north-east.

The relation between the model and the background network is shown below in **Error! Reference source not found.**.

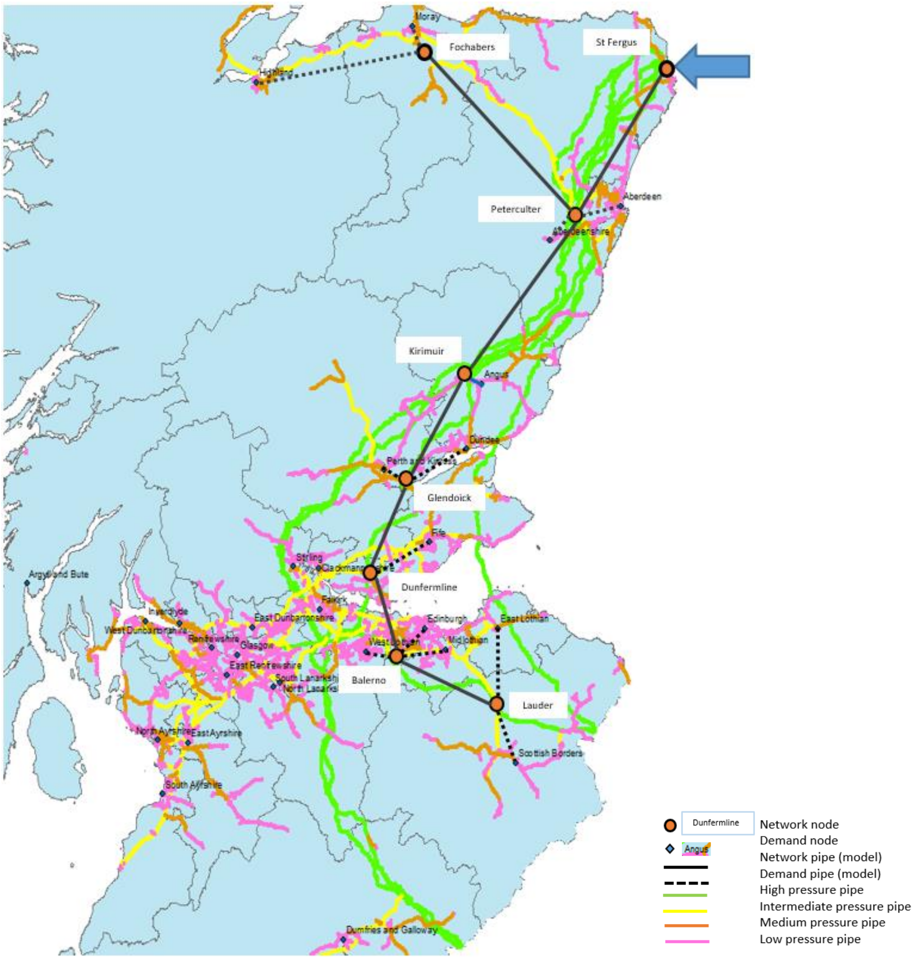

Figure 1 Network Schematic diagram superimposed on actual gas network.
Names in black are the demand nodes, representing local authorities and located at the town of local authority's head office, other than Aberdeenshire. Names on a white background are the network junction nodes, selected at a convenient location related to the real network.

The demand nodes were identified at the main town or city within each local authority, in which the local authority head office is based, or in one case another convenient town. Network nodes, defined as junctions without a demand, were created at appropriate points reflecting the real-life network as much as possible. All of these node points were defined by their National Grid coordinates, and were allocated a four letter name derived from the local authority name (for demand nodes) or the nearest town (network nodes) and a number. The pipes themselves were created simply as a straight line between the relevant National Grid coordinates.

2.2 Model Calculation Basis

The model is designed so that unlimited flow is available at the upstream end at a constant pressure, held at 8500kPa – the maximum operating pressure of transmission pipes, as described in section 1. The flow through the model is then driven by the demand, which is accumulated up the network from the downstream end.

The pressure loss in each transmission pipe is then found from equations of flow (section **Error! Reference source not found.**), based on the volume flow in the pipe and the upstream pressure, along with the pipe and fluid characteristics, starting at the top of the network with its fixed pressure. This then allows the downstream pressure in each pipe to be calculated, which is the same as the upstream pressure in the next pipe. This approach is possible because it is a simple 'tree' model, i.e. a central transmission 'trunk' with 'branches' off it, and no loops.

The upstream pressure in the demand pipes (based on Intermediate Pressure pipes) is in the real network governed by a pressure regulator to a maximum of 700kPa. This is modelled by setting the upstream node pressure to the lesser of the transmission pipe pressure at the same node, or 700kPa.

The flow velocity is found from the volume flow rate, which comes from the demand or cumulative demand, and the pipe cross sectional area.

2.3 Pipe Diameters

The modelled pipe diameters were set up using a manually iterative process, by running the model and identifying the minimum standard size commercially available pipe that would allow the pressure targets to be met with natural gas. This provides for a model which can deliver the current peak demand, but has little spare capacity. It does, by implication, have excess capacity at lower demand periods. The flow velocity was checked, and for each of the pipes in the network, it was found that the maximum flow velocity was well within the maximum flow velocity of 40 m/s [4]).

2.4 Equations of Flow

The equations of flow used are the Buzzelli solution to the Darcy Weisbach[13] flow equations.

The Buzzelli and Darcy Weisbach procedure calculates the pressure drop in a pipe, based on inputs including the pipe characteristics, the gas flow rate (determined by demand), and the gas viscosity and density. Because the density varies greatly with pressure, and the viscosity varies somewhat with pressure, this is an iterative process; the calculation must be repeated based on a changing assumed pressure drop until the calculated pressure drop equals the assumed pressure drop.

The Buzzelli solution takes the form:

$$\mathrm{B1} = \frac{(0.774.\ln(\mathrm{Re}) - 1.41)}{1 + 1.32.\left(\frac{\mathrm{ks}}{\mathrm{D}}\right)^{0.5}}$$

Equation 1

$$B2 = \frac{ks.Re}{3.7.D} + 2.51.B1$$

Equation 2

$$\frac{1}{{f_D}^{0.5}} = B1 - \frac{\left(B1 + 2.log_{10}\left(\frac{B2}{Re}\right)\right)}{1 + \left(\frac{2.18}{B2}\right)}$$

Equation 3

The Darcy Weisbach flow equation is

$$\Delta P = \frac{(L.f_D.\rho.V^2)}{2.D}$$

Equation 4

Where

L = length of pipe. Set in the model structure.
ks = Pipe roughness coefficient. Looked up from standard tables and set in the model structure.
D = pipe diameter. Set in the model structure, manually varied.
ΔP = change in pressure along pipe length. Iterated through the computation.
f_D = Darcy friction factor (also called the flow coefficient). Recalculated each iteration step.
P = pressure in pipe – taken as linear mean pressure. Recalculated each iteration step.
ρ = fluid density. Recalculated each iteration step, from look-up tables based on P.
μ = dynamic viscosity of the fluid. Recalculated each iteration step, from look-up tables based on P.
V = flow velocity. Recalculated each iteration step.
Re = Reynolds Number. Re = ρ.D.V/μ, recalculated each iteration step.

The commonly used solution to the Darcy Weisbach theory is the Colebrook – White equation [13]. However, that is itself an iterative calculation, so the analysis would require a double iteration due to the variation of density and viscosity with pressure, which would be more computationally complex. Within this project, a separate comparison was made between the Buzzelli calculation and the Colebrook-White method; the results were found to agree to an accuracy of better than 0.1% for the flow ranges under consideration, which is more than adequate for these purposes.

2.5 Demands

Demand data was set up at each of the node points by combining a number of sources. The population of each local authority was obtained from the Scottish Government, along with the gross annual gas usage for Scotland. These were combined to produce an annual average consumption for each local authority in proportion to its population, which was converted into an average daily consumption. This average daily consumption figure was converted into an hourly demand profile based on standard variation curves provided by Scotland Gas Networks. This gave a 24 hour demand profile as shown in **Error! Reference source not found.**.

Calculated hourly energy demand at each demand node, over 24 hours.
Values in MWh/hour (i.e. hourly average MW).

Hr.	ND26_ Wlot	ND27_ Edin	ND28_ Mlot	ND29_ Elot	ND31_ Fife	ND32_ Dund	ND33_ Angs	ND34_ Absh	ND35_ Abdn	ND36_ Mory	ND37_ High	ND39_ Pkin	ND46_ Sbor
1	92.7	265.8	46.8	54.2	189.2	75.6	58.8	132.3	115.8	48.5	119.4	77.0	58.5
2	61.8	177.2	31.2	36.2	126.1	50.4	39.2	88.2	77.2	32.4	79.6	51.3	39.0
3	61.8	177.2	31.2	36.2	126.1	50.4	39.2	88.2	77.2	32.4	79.6	51.3	39.0
4	61.8	177.2	31.2	36.2	126.1	50.4	39.2	88.2	77.2	32.4	79.6	51.3	39.0
5	71.1	203.8	35.9	41.6	145.0	58.0	45.1	101.4	88.8	37.2	91.6	59.0	44.9
6	120.5	345.6	60.9	70.5	245.9	98.3	76.5	172.0	150.5	63.1	155.3	100.0	76.0
7	268.9	770.9	135.8	157.3	548.6	219.3	170.7	383.6	335.8	140.7	346.3	223.2	169.6
8	309.1	886.1	156.1	180.8	630.6	252.1	196.2	440.9	386.0	161.7	398.1	256.5	195.0
9	247.3	708.9	124.9	144.6	504.4	201.6	156.9	352.7	308.8	129.4	318.5	205.2	156.0
10	216.4	620.3	109.3	126.5	441.4	176.4	137.3	308.7	270.2	113.2	278.7	179.5	136.5
11	200.9	576.0	101.5	117.5	409.9	163.8	127.5	286.6	250.9	105.1	258.8	166.7	126.7
12	200.9	576.0	101.5	117.5	409.9	163.8	127.5	286.6	250.9	105.1	258.8	166.7	126.7
13	200.9	576.0	101.5	117.5	409.9	163.8	127.5	286.6	250.9	105.1	258.8	166.7	126.7
14	200.9	576.0	101.5	117.5	409.9	163.8	127.5	286.6	250.9	105.1	258.8	166.7	126.7
15	200.9	576.0	101.5	117.5	409.9	163.8	127.5	286.6	250.9	105.1	258.8	166.7	126.7
16	253.4	726.6	128.0	148.2	517.1	206.7	160.8	361.6	316.5	132.6	326.4	210.3	159.9
17	278.2	797.5	140.5	162.7	567.5	226.9	176.5	396.8	347.4	145.6	358.3	230.8	175.5
18	293.6	841.8	148.3	171.7	599.0	239.5	186.3	418.9	366.7	153.7	378.2	243.7	185.2
19	247.3	708.9	124.9	144.6	504.4	201.6	156.9	352.7	308.8	129.4	318.5	205.2	156.0
20	231.8	664.6	117.1	135.6	472.9	189.0	147.1	330.7	289.5	121.3	298.6	192.4	146.2
21	216.4	620.3	109.3	126.5	441.4	176.4	137.3	308.7	270.2	113.2	278.7	179.5	136.5
22	154.5	443.0	78.0	90.4	315.3	126.0	98.1	220.5	193.0	80.9	199.0	128.3	97.5
23	123.6	354.4	62.4	72.3	252.2	100.8	78.5	176.4	154.4	64.7	159.2	102.6	78.0
24	92.7	265.8	46.8	54.2	189.2	75.6	58.8	132.3	115.8	48.5	119.4	77.0	58.5

2.6 Model code and functionality

The flowchart in Figure 2 below outlines the function of the code.

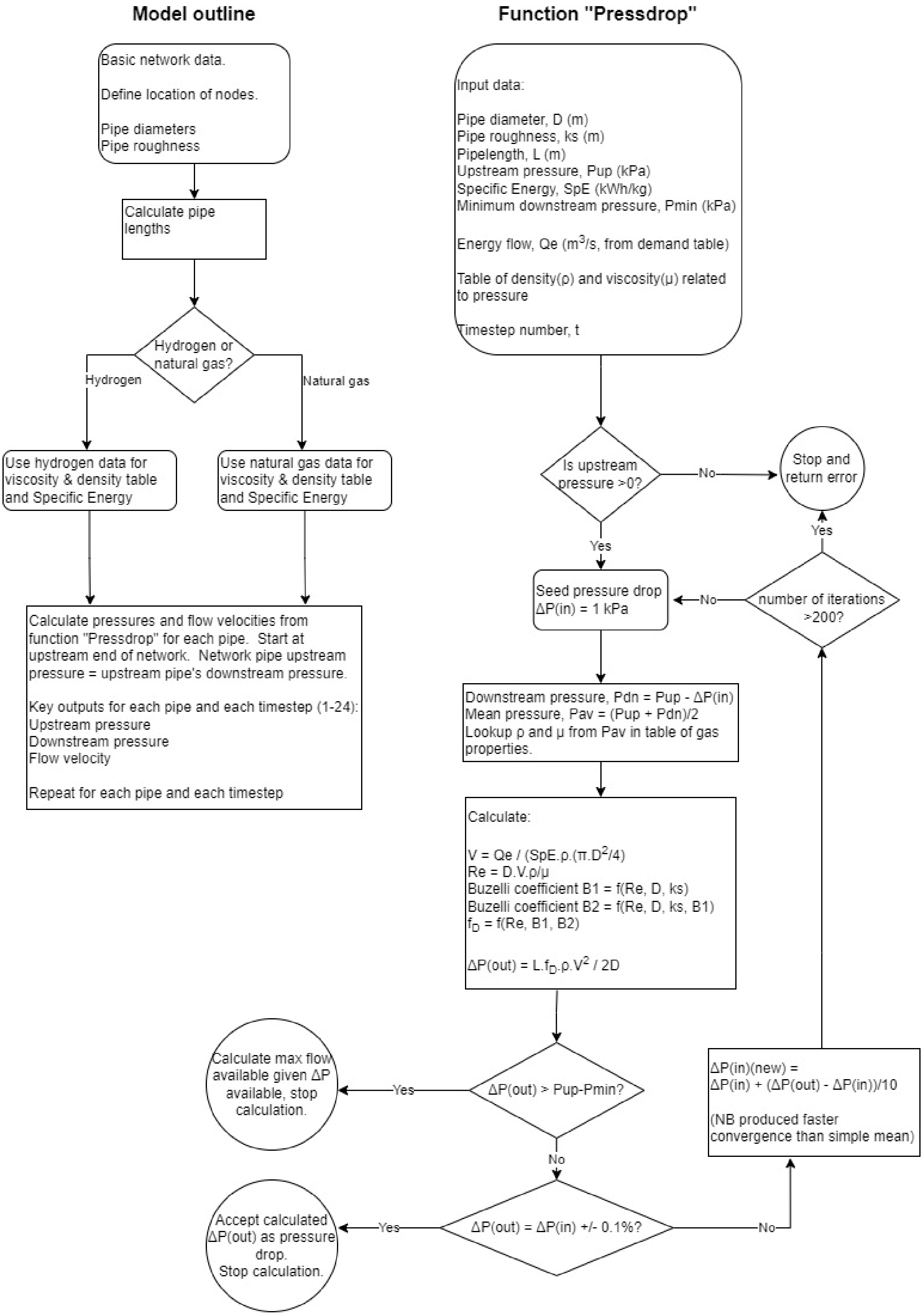

Figure 2 Model code schematic.
Core functions only are shown, not presentation of outputs or summing of aggregate pipe values. The model code that this represents is available at https://github.com/J-M-Low/Hydrogen_pipe_capacity

2.7 **Test with Hydrogen**

The model was initially created as above to represent a network capable of supplying enough natural gas to meet demand. It was then re-calculated with hydrogen as a gas in the same pipes; this was simulated by using the density, viscosity and specific energy appropriate to hydrogen instead of to natural gas. Thus the modelled quantities of hydrogen delivered the same energy demand as for natural gas.

3 Results

3.1 **Initial Setup**

The process of setting up the pipes gave the dimensions and peak flow pressures and velocities for natural gas shown in

Table 1.

Pipe name	Diameter (m)	Length (m)	Upstream Pressure (kPa)	Downstream pressure (kPa)	pressure drop (kPa)	Velocity (m/s)
Network pipes						
PN00_Sfeg_Petc	0.5	57,558	8500	7241	1259	6.07
PN01_Petc_Foch	0.25	76,121	7241	6012	1228	3.72
PN02_Petc_Kiri	0.45	65,160	7241	5778	1463	6.42
PN03_Kiri_Glen	0.45	39,357	5778	4795	982	7.60
PN04_Glen_Dunf	0.45	35,503	4795	4050	746	7.64
PN05_Dunf_Balo	0.4	22,717	4050	3487	563	8.43
PN06_Balo_Laud	0.25	41,028	3487	2774	713	5.74
Demand pipes (upstream pressure capped at 700kPa)						
PD19_Petc_Abdn	0.35	11,950	700	460	240	17.21
PD20_Petc_Absh	0.4	15,328	700	501	199	14.55
PD21_Foch_Mory	0.25	13,801	700	400	300	14.91
PD22_Foch_High	0.5	69,400	700	435	265	8.85
PD23_Kiri_Angs	0.25	7,811	700	474	226	16.85
PD24_Glen_Dund	0.35	26,549	700	458	242	11.24
PD25_Glen_Pkin	0.25	3,500	700	541	159	20.96
PD26_Dunf_Fife	0.45	22,883	700	318	382	19.37
PD27_Balo_Wlot	0.3	11,032	700	360	340	20.55
PD28_Balo_Edin	0.45	12,485	700	300	400	27.77
PD29_Balo_Mlot	0.25	16,890	700	336	364	15.23
PD30_Laud_Elot	0.3	26,331	700	415	285	11.37
PD31_Laud_Sbor	0.3	16,600	700	510	190	11.25

Table 1 Initial model setup of pipe diameter, length, and corresponding pressures, with natural gas. Note that where more than 700 kPa is available upstream of a demand pipe, it is regulated down to 700 kPa in accordance with gas operating companies operating practice [3]. It can also be seen that the flow velocities are well within the 40m/s limit.

3.2 Hydrogen Pressure Drops

3.2.1 Network Pipes

We can see from Table 2 below that when the network is converted to hydrogen, the pressure drop in each pipe is greater than when it is used for natural gas. This effect is cumulative down the network pipes, meaning that in the southern (downstream) end of the network the available pressure at the upstream end of the demand pipes is lower than the 700 kPa requirement for serviceability. The higher flow velocity is the main contributor to the additional pressure loss. This is a function of the low density of hydrogen.

Clearly some method of boosting the pressure will be required. Trials of (1) a single pressure boost at the upstream end of the low pressure zone, and (2) multiple small pressure boosts distributed along the length of the pipe were carried out. The outcomes of these are also set out in Table 2 below.

	Peak demand – hydrogen No additional pressure boost.				***Peak demand – hydrogen Trial 1 - Single boost.***				***Peak demand – hydrogen Trial 2 - Multi boost.***			
Pipe name	***Up-stream (kPa)***	***Down-stream (kPa)***	***pressure drop (kPa)***	***Velocity (m/s)***	***Up-stream (kPa)***	***Down-stream (kPa)***	***pressure drop (kPa)***	***Velocity (m/s)***	***Up-stream (kPa)***	***Down-stream (kPa)***	***pressure drop (kPa)***	***Velocity (m/s)***
PN00_ Sfeg_Petc	8500	6143	2357	28.11	8500	6143	2357	28.11	8500	6143	2357	28.11
PN01_ Petc_Foch	6143	3194	2949	21.74	6143	3194	2949	21.74	6143	3194	2949	21.74
PN02_ Petc_Kiri	6143	2450	3693	39.84	6143	2450	3693	39.84	6143	2450	3693	39.84
PN03_ Kiri_Glen	2450	0	2450	74.45	**7000**	5640	1360	25.72	**5000**	2841	2159	40.87
PN04_ Glen_Dunf	0	0	0	0	5640	4602	1038	25.82	**4000**	2333	1667	41.50
PN05_ Dunf_Balo	0	0	0	0	4602	3799	803	29.11	**3500**	2354	1146	41.59
PN06_ Balo_Laud	0	0	0	0	3799	2716	1083	20.84	**3500**	2280	1220	23.48

*Table 2 Comparison of pressure drops with hydrogen, network pipes only, with initial conditions and pressure boosted on the network pipes. Boosted pressures shown in **shaded bold**.*

We can see from this that both of these approaches appear viable. The best one to take in reality would depend on a more detailed analysis of the real life circumstances, which is beyond the scope of this study. We can also see that the maximum flow velocity only slightly exceeds the maximum; the acceptability of this will require further investigation, but the lower density and viscosity of hydrogen *might* mean that it entrains less scour-causing dust, making a higher velocity acceptable.

3.2.2 Demand Pipes

Once the upstream pressure in the demand pipes is high enough (i.e. 700 bar) then there is adequate pressure to provide enough hydrogen at about half of the demand points at the minimum allowable pressure of 200kPa. However in some cases this is not possible. Two solutions were trialled: an increase in pipe capacity by the simple expedient of increasing the upstream pressure; and the provision of downstream storage. These are shown in Table 3.

Pipe	*Peak demand – hydrogen – Upstream pressure set to 700 kPa*			*Peak demand – hydrogen – Upstream pressure set to 850 kPa*			*24 hour demand & delivery – hydrogen. Qe = Energy flow rate. Upstream pressure fixed at 700 kPa.*				
	Up-stream (kPa)	*Down-stream (kPa)*	*Velocity (m/s)*	*Up-stream (kPa)*	*Down-stream (kPa)*	*Velocity (m/s)*	*Qe demand (MWh/ day)*	*Calc. max Qe (kWh/s)*	*Max Qe (MWh/ day)*	*Factor of safety*	*Mean velocity (m/s)*
PD19_ Petc_Abdn	700	280	71.13	850	556	49.77	5,504	112.5	9,721	177%	34.79
PD20_ Petc_Absh	700	373	56.44	850	608	41.76	6,288	139.7	12,073	192%	29.42
PD21_ Foch_Mory	**700**	**200**	**72.78**	850	483	42.74	2,306	42.8	3,699	160%	30.59
PD22_ Foch_High	700	211	38.25	850	524	25.52	5,677	110.6	9,557	168%	18.01
PD23_ Kiri_Angs	700	312	68.00	850	570	48.93	2,797	58.4	5,044	180%	34.33
PD24_ Glen_Dund	700	273	46.44	850	551	32.49	3,594	72.9	6,295	175%	19.18
PD25_ Glen_Pkin	700	445	79.69	850	656	60.49	3,658	90.3	7,799	213%	36.29
PD26_ Dunf_Fife	**700**	**200**	**80.37**	850	386	55.59	8,992	153.3	13,245	147%	25.99
PD27_ Balo_Wlot	**700**	**200**	**92.34**	850	440	58.41	4,407	78.3	6,762	153%	28.08
PD28_ Balo_Edin	**700**	**200**	**111.6**	850	368	79.28	12,636	212.9	18,398	146%	36.69
PD29_ Balo_Mlot	**700**	**200**	**65.19**	850	402	43.85	2,226	38.3	3,312	149%	20.81
PD30_ Laud_Elot	**700**	**200**	**57.51**	850	500	32.68	2,578	48.7	4,208	163%	14.66
PD31_ Laud_Sbor	700	381	44.37	850	614	32.83	2,780	62.7	5,413	195%	15.10

Table 3 Demand pipes pressure drop with hydrogen at peak flow.
Entries in ***bold*** *show where the minimum allowable downstream pressure is reached, meaning that insufficient hydrogen can be delivered to meet demand within the pressure requirement. Note the peak flow velocities generally become very high in these pipes due to the lower pressure than network pipes, although the mean flow velocity in the event of storage is within normal limits.*

Increasing the upstream pressure helps in two ways. The first is more obvious: more pressure available means that given the losses due to flow, more pressure is available downstream. The second is more subtle: by operating the pipe at a higher pressure, the gas density increases. Therefore the same mass of gas – and hence energy – can be transferred at a lower volume flow rate. This means the flow velocity is lower, leading to lower pressure loss due to flow. This is why flow velocities are lower at higher pressure. Nevertheless, even at higher pressures there are several pipes which exceed 40 m/s flow velocity by a substantial margin.

A relatively small increase in upstream pressure from 700 kPa to 850 kPa was enough to overcome the additional losses through the demand pipes. This is still within the European standard pressure rating of such pipes of 10bar / 1,000 kPa [14], and in usual practice could be achieved from the pressure available in the transmission pipe rather than requiring an active booster pump. However, there may be other operating factors preventing the widespread adoption of this higher pressure rating – including lack of certainty of the pressure capacity of pipes installed many years ago.

The downstream storage requirement is not explicitly modelled; instead, a separate analysis was made of the maximum capacity of each pipe, given the specified upstream pressure. The maximum daily delivery of the pipe was then calculated as that maximum capacity multiplied by 24 hours. In every case, the maximum capacity so calculated exceeds the total 24-hour demand by a factor of at least 1.46. Also, the mean velocity required to deliver the required quantity is always within the 40 m/s operating practice limit. This indicates that the lack of capacity to meet the highest hourly demand can be addressed by the provision of a downstream local storage facility of less than 24 hours' capacity**.** Due to the issue of flow velocity, the downstream storage is likely to be a more robust solution than operating at increased pressure.

3.3 **Correlation and Prediction**

Figure 3 and Figure 4 show the relative velocities of natural gas and hydrogen in each pipe.

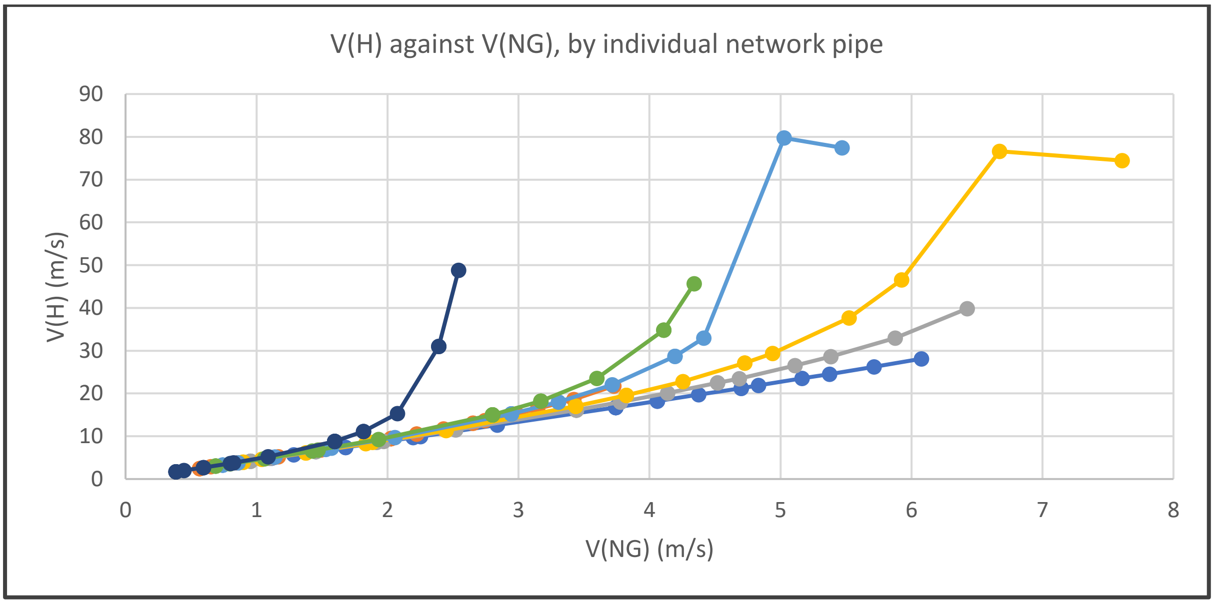

Figure 3 Flow velocity of hydrogen against flow velocity of natural gas, network pipes.
Each data point represents a one-hour time increment in a single pipe. Each line represents the 24 hour flow pattern of a single pipe, although identifying the individual pipes is not important at this stage.

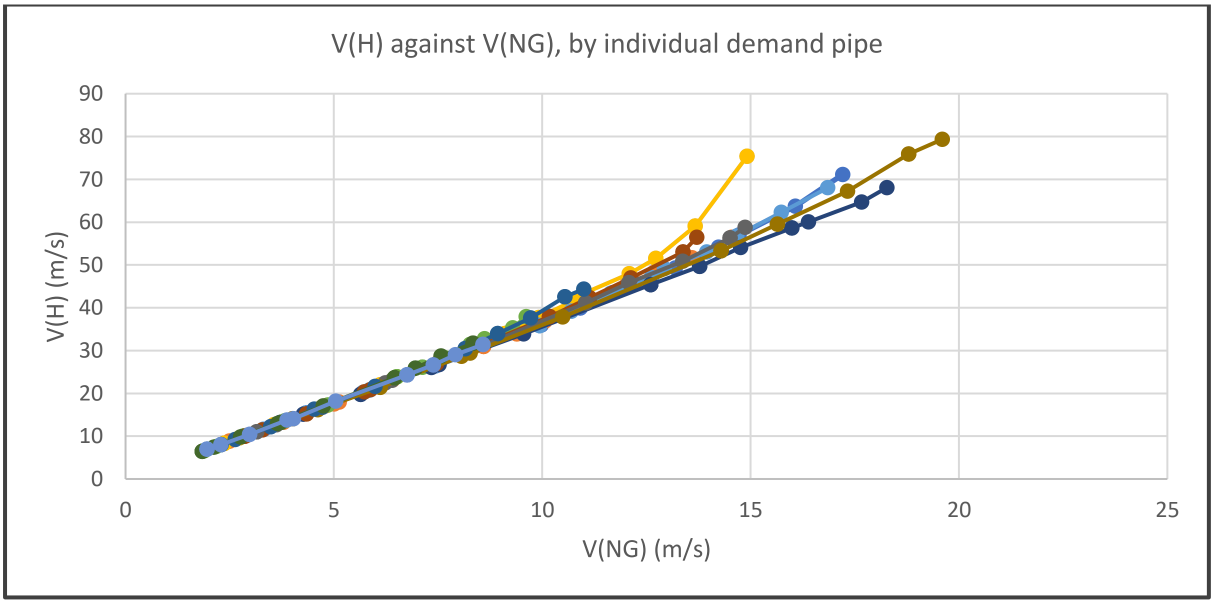

Figure 4 Flow velocity of hydrogen against flow velocity of natural gas, demand pipes.
Each data point represents a one-hour time increment in a single pipe. Each line represents the 24 hour flow pattern of a single pipe, although identifying the individual pipes is not important at this stage.

It can be seen clearly that there is a minimum gradient to these. This represents the multiple by which hydrogen flow velocity is greater than natural gas flow velocity - around 3.6 for demand pipes and 4.4 for network pipes. This is due to the difference in specific energy (natural gas: 13.9 kWh/kg, hydrogen 36.35 kWh/kg, a factor of 2.6) and density. At higher pressure ranges, the density difference is a factor of up to 11.5 (natural gas / hydrogen); at the lower ranges it is around 9.1. The minimum gradients then are found from:

$$V_h = \frac{V_{ng} . \rho_{ng} . SpE_h}{\rho_h . SpE_{ng}}$$

Equation 5

Where

V = velocity (m/s)
ρ = density (kg/m3)
SpE = Specific Energy (kWh/kg)
(h) denotes Hydrogen
(ng) denotes Natural Gas

This suggests that there is some correlation between the existing natural gas regime flow and pressure and the likelihood of a pipe being unable to deliver the required energy via hydrogen. Understanding this could enable easier forecasting of which pipes to prioritise for intervention, such as pressure boost or additional downstream storage.

Pearson correlation coefficients [15] were calculated for each potential natural gas parameter which might cause the hydrogen delivery capacity to be exceeded.

The Pearson correlation coefficient is found from the equation

$$\text{pcc} = \frac{\sum[(x_i - \overline{x}).(y_i - \overline{y})]}{(\text{n} - 1).s_x.s_y}$$

Equation 6

Where

pcc = Pearson Correlation Coefficient
x_i is the individual value of the parameter being considered
$\bar{x}$ is the mean value of the parameter being considered
y_i the individual value of the parameter to be forecast
$\bar{y}$ is a mean value of the parameter to be forecast
n is the number of samples in the data set
s_x is the standard deviation of parameter x
s_y is the standard deviation of parameter y.

The result of this calculation is a single value between 1 (positive correlation) and -1 (negative correlation), for each parameter. A strong correlation between the two parameters gives a result close to either -1 or 1; the closer the result to zero, the weaker the correlation.

The parameter to be forecast was created as the flow exceedance ratio (FER), defined as

FER = Q_m(demand) / Q_m(max)

Equation 7

Where Q_m(demand) is the mass flow demand, derived from the energy demand profile, and Q_m(max) is the maximum mass flow given the pipe and fluid characteristics, and the upstream pressure.

The Pearson correlation coefficient for a number of parameters potentially relating to the FER(h), as shown in Table 4:

Parameter (NB. ng = natural gas)	**pcc**
Area/Length	-0.051
Q_m(demand) (ng)	0.112
Q_m(max) (ng)	-0.262
Q_m(demand) / Q_m(max) (ng)	0.836 (= FER(ng))
V(ng)	0.666
Re(ng	0.189
V(max)(ng)	-0.101
Re(max)(ng)	-0.279

Table 4   Pearson correlation coefficients, various potential forecasting parameters.

Q_m = mass flow rate
V = flow velocity
Re = Reynold's number
V(max) = maximum flow velocity
Re(max) = maximum Reynold's number.

Clearly, there is a fairly strong correlation between the FER(ng) and FER(h). There is also a moderately strong correlation with V(ng).

Charting FER(h) against FER(ng) produces Figure 5:

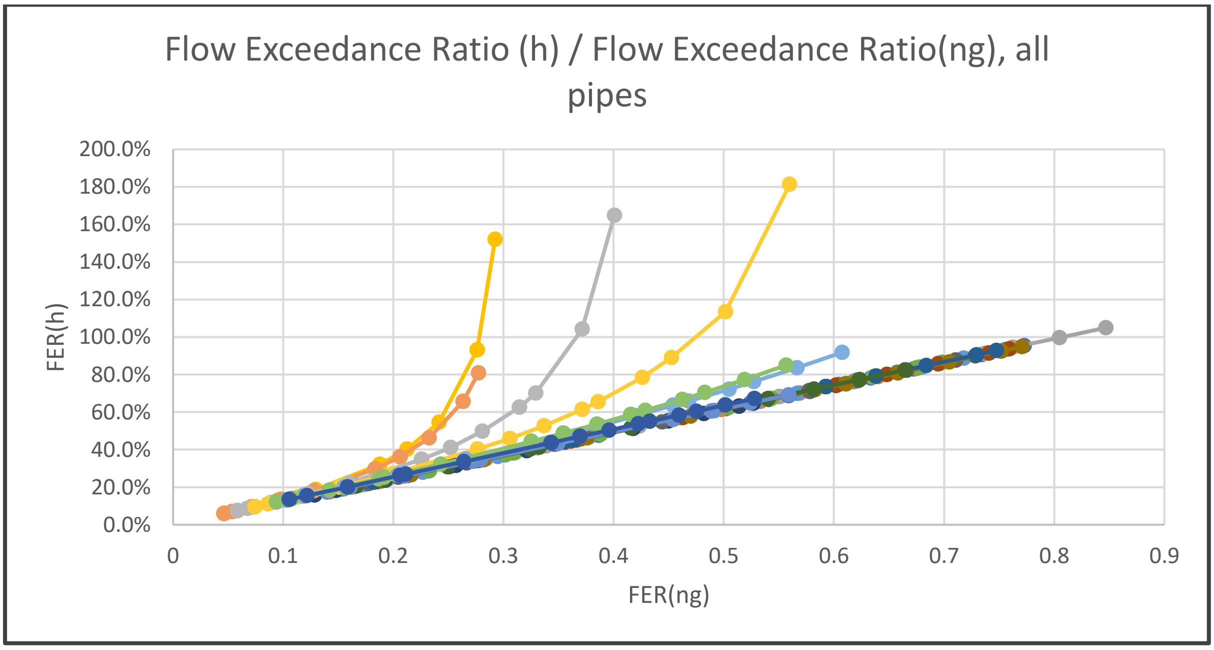

Figure 5   Chart showing FER(h) against FER(ng).
Each data point represents a one-hour time increment in a single pipe. Each line represents the 24 hour flow pattern of a single pipe, although identifying the individual pipes is not important at this stage.

The solid base line of minimum gradient includes all the demand pipes. This passes through the point FER(ng) = 0.8, FER(h) = 1.0. Where the FER exceeds 1.0, the demand is greater than the maximum possible supply, and the pipe fails. This corresponds to the 20% lower energy delivery for hydrogen identified by Dodds & Demoulin [7], discussed in the introduction above. The upward 'tails' are where the network pipes begin to fail to deliver the required quantity of hydrogen. A key observation here is that the demand pipes are modelled at a fixed upstream pressure, while the network pipes have a gradually reducing pressure upstream pressure further downstream. This is connected to the demand pipes showing a consistent ratio in Figure 5, while the network pipes do not.

This was normalised for pressure by plotting FER(h).Pup(h) against FER(ng).Pup(ng), where Pup is pressure upstream. With some experimentation, this became FER(h).Pup(h)$^{1.1}$ against FER(ng).Pup(ng)$^{1.1}$ to achieve a closer correlation. This is shown below in Figure 6.

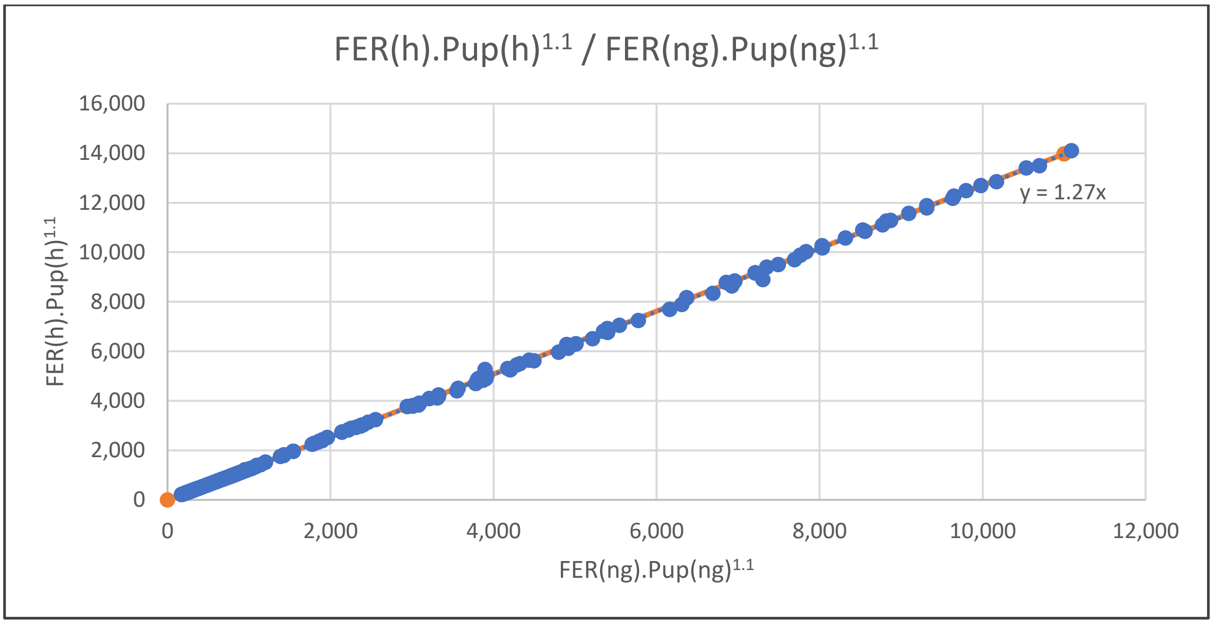

Figure 6 FER(h).Pup(h)1.1 against FER(ng).Pup(ng)1.1.

This shows a very strong correlation, which can be expressed as:

$$\mathrm{FER_h}.\,\mathrm{Pup_h^{1.1}} = 1.27.\,\mathrm{FER_{ng}}.\,\mathrm{Pup_{ng}^{1.1}}$$

Equation 8

However, Equation 8 is not fully predictive of FER_h, as it requires knowledge of Pup, the upstream pressure. We need to know when FER_h will exceed 100%, without knowledge of other factors relating to hydrogen.

Charting Pup_h against Pup_{ng}, restricted to network pipes, produces Figure 7:

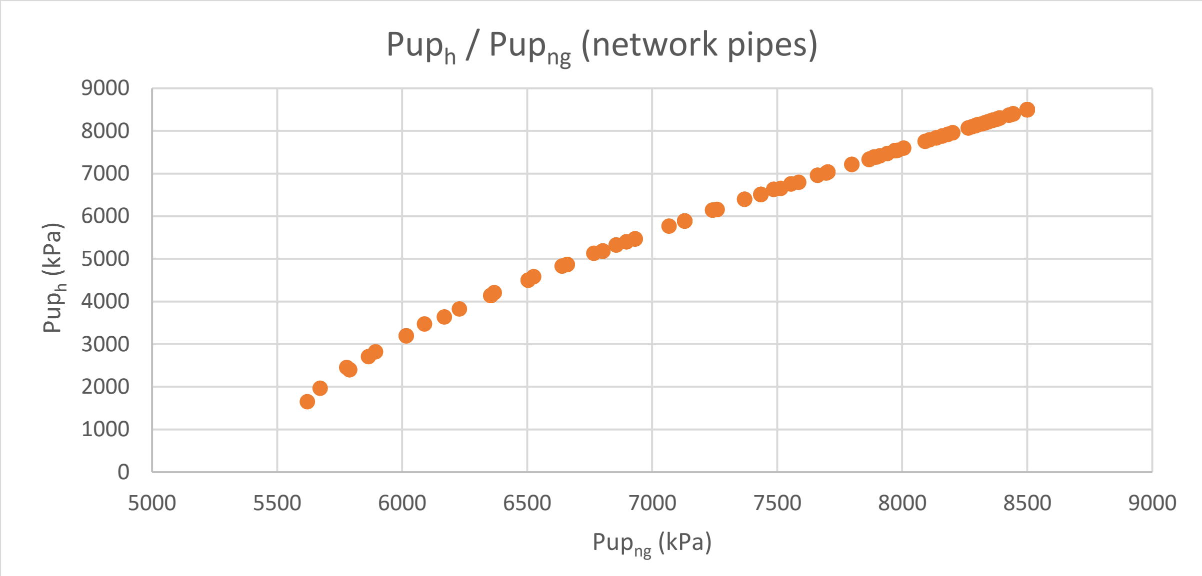

Figure 7 Pup_h against Pup_{ng}. Pup = Pressure upstream

It appears that there is a relationship. After some experimenting, a close correlation between $Pup_h^{1.85}$ and $Pup_{ng}^{1.85}$ was found – as shown in Figure 8:

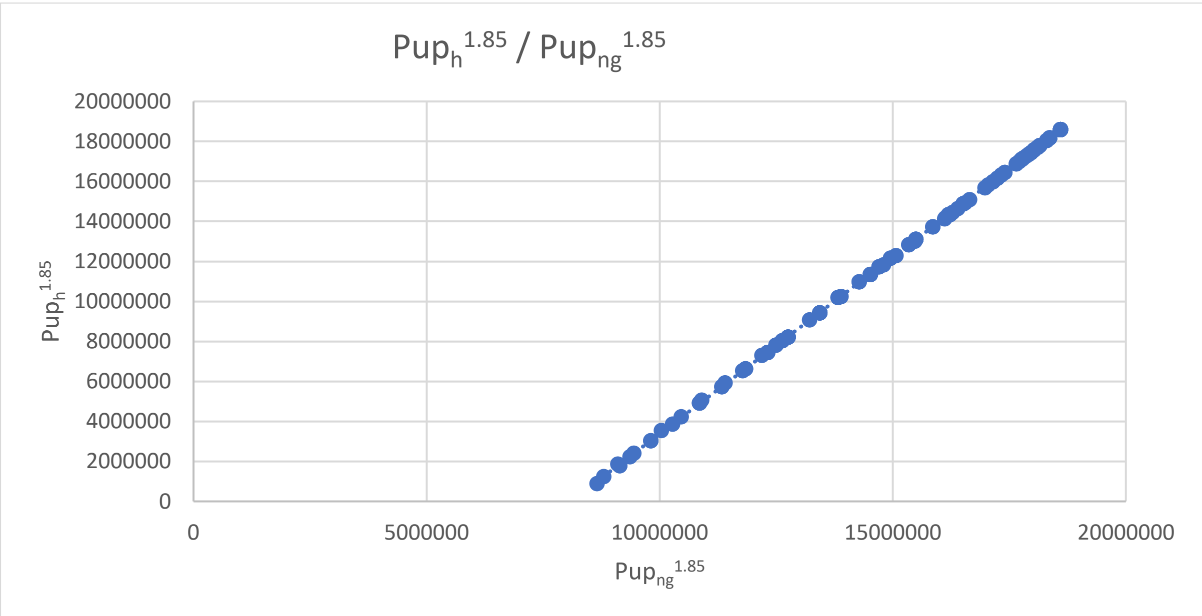

Figure 8 Pup_h1.85 against Pup_{ng}1.85

It is necessary to introduce a note of caution here: there is no obvious reason why a power of 1.85 should be used, so this can only be taken as an empirical observation that happens to fit this particular data set well. The same applies to the power 1.1 used in Figure 6 above. Further investigation will be required to confirm or consider how broadly applicable these values are.

However, given that caveat, this correlation is represented as:

$$Pup_h^{1.85} = 1.768. Pup_{ng}^{1.85} - 14.3 \times 10^6$$

Equation 9

By calculating the Pup_h from that formula for network pipes then substituting it for the relationship shown in Figure 6, the following relationship is found:

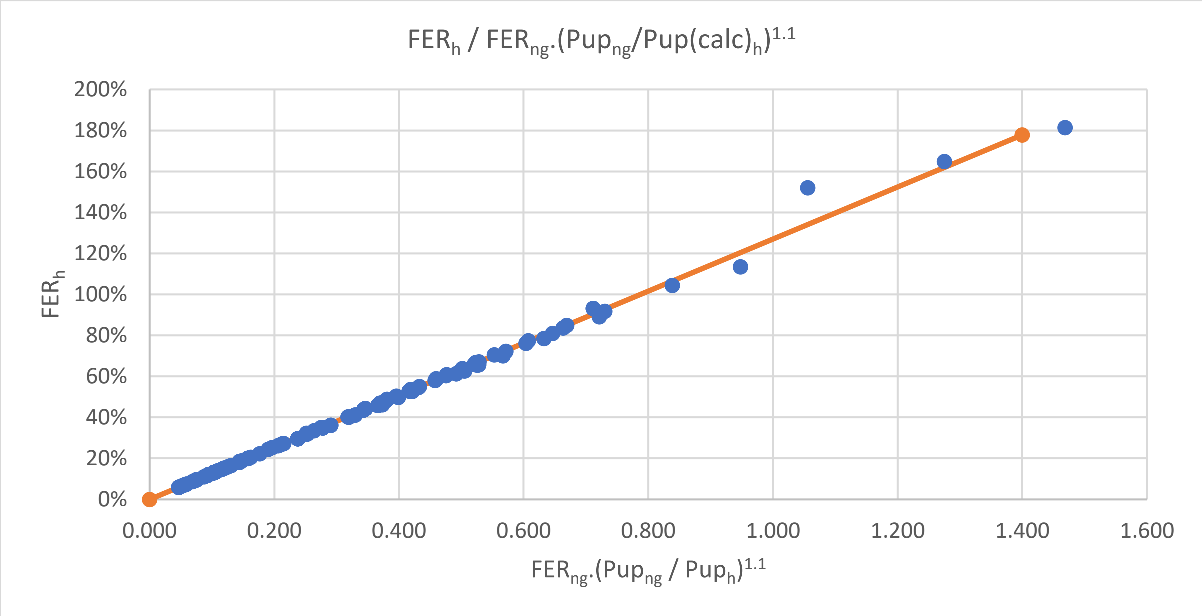

Figure 9 *FER_h against $FER_{ng}.(Pup_{ng}/Pup_h)^{1.1}$, where Pup_h is found from Equation 9 above.*
There is some scatter in the higher reaches of this chart; this is past the FER_h = 100% level, so will not affect the result.

We can simply rearrange Equation 8 here to:

$$FER_h = 1.27. FER_{ng}. \left(\frac{Pup_{ng}}{Pup_h}\right)^{1.1}$$

Equation 10

Where Pup_h is found from the rearranged Equation 9:

$$Pup_h = \left(1.768. Pup_{ng}^{1.85} - 14.3 \times 10^6\right)^{0.541}$$

Equation 11

And clearly, from Figure 9 and Equation 10, when $FER_{ng}.\left(Pup_{ng}/Pup\_h\right)^{1.1}$ exceeds 0.79, then the FER_h will exceed 100%, and the pipe will be unable to deliver the quantity of hydrogen required.

4 Discussion and Conclusion

4.1 Model Construction

In terms of the model construction, this worked well. While obviously it cannot replicate the real world situation, it provides a big enough range of scenarios to provide some insight into the expected behaviour of a real network.

A key assumption in the model construction has been to use a specific energy value for hydrogen of 36.35 kWh/kg. This is the average of the Lower Heat Value (LHV) of 33.3 kWh/kg [16] and Higher Heat Value (HHV), 39.4 kWh/kg [17]. This approach was adopted because of the likely mixed use of the hydrogen: a modern condensing boiler would be able to recover the heat of condensation, so the higher heat value would apply. However, an open flame such as a gas cooker, or a fuel cell application such as vehicle fuel or backup electricity generation, would generally not, so the LHV would apply. As the hydrogen supplied through the network would be for mixed use, with hard to forecast proportions, a mid value between the two has been used. If a different value of specific energy were found to be more appropriate, this would affect some of the values and factors found in this analysis, but would not change the fundamental findings.

4.2 Energy Delivery with Hydrogen

Some pipes turned out to be unable to deliver enough hydrogen within the maximum allowable upstream pressure and the minimum acceptable downstream pressure. Where there is a shortfall in capacity this might be addressed by either (1) increasing pipe capacity through additional or replacement pipes, (2) by increasing the upstream pressure, or (3) providing short term (< 24 hours) downstream storage. The issue appears at peak demand but not throughout the day, so filling short term storage at the lower demand periods would be a viable way of ensuring that enough hydrogen can be delivered.

In demand pipes, for every pipe analysed there was a comfortable excess in 24 hour capacity to deliver hydrogen over the 24-hour demand. This indicates that this should be a viable strategy. This would be required at the downstream end of the pipes, to keep the flow velocity lower (see Table 3). Boosting the upstream pressure in the demand pipes to 850 kPa could also resolve the problem. However, this runs the risk of exceeding the pressure rating of older pipes (although they may need to be replaced anyway if the material is unsuitable for hydrogen), and the peak flow velocity would often exceed the maximum allowable (see also Table 3). Given that one or both of these solutions should be viable, it should not be necessary to enlarge the actual pipe capacity.

In network pipes, the inadequate delivery appears to be more appropriately addressed by boosting the pressure at the upstream end of the affected section. In these pipes, the higher operating pressure increases the hydrogen density enough to keep the flow velocity within tolerance. This could be appropriately done through a series of smaller pressure boosting stations, or a single larger one, depending on a detailed assessment of the real life situation.

The flow velocity of hydrogen is at least 3.6x that for natural gas in the demand pipes; it is higher, at least 4.4x higher in network pipes (see Figure 3 and Figure 4), because natural gas is more compressible than hydrogen. At peak times this leads to very high flow velocities approaching 80 m/s, or more in cases where full delivery is not possible (Table 3). Further study will be required to identify whether or not this is acceptable for the characteristics of hydrogen; if not, then downstream storage or operation at higher pressure will be required to ensure that enough hydrogen can be delivered at acceptable flow velocities.

4.3 **Predicting the need for intervention**

It is possible to predict the natural gas pipes that will require intervention – in the form of pressure boost or downstream storage – when used to supply hydrogen.

The first step is to calculate a forecast hydrogen upstream pressure (Pup) for the network pipes from the natural gas pressure, using Equation 11:

$$Pup_h = \left(1.768.\,Pup_{ng}^{1.85} - 14.3 \times 10^6\right)^{0.541}$$

For demand pipes, this does not apply because the upstream pressure is constrained by being actively reduced from that delivered by the network pipes to 700 kPa (in current standard practice).

The calculated or constrained Pup(h) is then used to find the maximum flow capacity of the pipe using the Buzzelli and Darcy-Weisbach procedure, which requires an iterative process using equations 1 to 4 (section 2.4).

The calculated Pup(h) is also used in the flow exceedance ratio calculation, Equation 10:

$$FER_h = 1.27.\,FER_{ng}.\left(\frac{Pup_{ng}}{Pup\_h}\right)^{1.1}$$

The result is the Flow Exceedance Ratio for hydrogen, that is the mass flow demand relative to the maximum capacity of the pipe. If this exceeds 100%, the pipe will be unable to deliver the quantity of hydrogen required without intervention as described above.

4.4 **Testing the Hypotheses**

The starting hypotheses were:

1. The natural gas network can be converted to supply enough pure hydrogen to replace all natural gas in use, on the basis of energy transported, without enlargement or replacement of the pipes.
2. It will be possible to identify which parts of a network will need intervention when converted to supply hydrogen, on the basis of the natural gas characteristics alone.

These appear to be confirmed, albeit with caveats - some other modification will be required. This model has been deliberately set up on the basis of having little excess capacity. In these circumstances, it seems unlikely that the network can be changed over with no modification. If in a real situation there is more excess capacity, the change should be considerably easier.

However, these findings should be taken as a starting point for further analysis or confirmation, rather than a definitive global answer. The analysis in this paper is based on the operating regime in one country, with specific assumptions about pressure management and the effective specific energy of hydrogen (ie. the use case balance between HHV and LHV). Further analysis, taking account of local variations in these factors, would be necessary before applying these methods or findings more broadly.

The finding in Abbas at al [8] that an increased volume flow of around 3x that required for natural gas was also considered. In fact we found a higher volume flow increase factor of around 3.6, in demand pipes, to upwards of 4.4 in network pipes. This increased value is due to the greater compressibility of natural gas than hydrogen; Abbas et al carried out their analysis at standard temperature and pressure, so our conclusions are mutually consistent.

The finding in Dodds and Demoulin [7] that energy delivery capacity would be reduced by about 20% is borne out – the maximum capacity of a pipe to deliver hydrogen corresponds to about 80% of the capacity to deliver natural gas. This is illustrated in Figure 5.In conclusion, even in the limited excess capacity scenario tested it should be possible to use the existing pipe network as stated in the hypothesis. This will require a combination of other modifications, including the addition of targeted local storage, pressure boosts within the network, and/or operating at slightly higher pressures than current standard practice.

The Python code for the model used is available at:
https://github.com/J-M-Low/Hydrogen_pipe_capacity .

4.5 Further Study

This paper examines a hypothetical network, using the operating procedures applicable to existing natural gas networks in the UK. While the general principles should be more widely applicable, specific local factors should be taken into account. These will include:

- standard operating pressure regimes;
- mix of use cases leading to the effective average heating value of hydrogen;
- Local pipe materials and therefore applicable roughness coefficients;
- Leakage;
- Single or multiple injection points to the network.

This analysis is also limited to the higher pressure parts of a network, upstream of the connections to customers. Further modelling work should also be carried out to understand the impact on the lower pressure flow regimes up to the point of connection. If there is a substantial need for storage at that level, then the cost and complexity might increase significantly. However, it is encouraging to note that in this study, along with Abbas et al [8], the velocity increase factor reduces as pressure reduces – this leads to a smaller decrease in carrying capacity, which implies that less intervention in the low pressure network would be necessary.

The acceptability of higher flow velocities should be assessed. It is conceivable that hydrogen will have less capacity to transport dust, which leads to scour damage to the inside of pipes. If so, higher flow velocities may be acceptable. This might involve experimentation and collaboration with pipe manufacturers.

Further modelling should examine the effect of linepack storage, that is storing additional mass of gas inside the pipes by varying the operating pressure and hence the density – a simple comparison of compressibility suggests that the linepack storage capacity of hydrogen will be about 25% that of natural gas [7]. However, it is important to understand how much is actually needed compared to how much surplus capacity there is available at present. This will be determined by local factors in any real network under consideration.

A similar analysis examining the effect of a mixed 20% hydrogen, 80% natural gas would also inform the transitional position.

5 Acknowledgements

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