SYSTEM OPTIMISATION OF GAS TRANSMISSION PIPELINES

Michael Kasch, ILF Consulting Engineers Germany GmbH, presents a two-step approach for gas pipeline optimisation, applied to hydrogen.

Due to the many parameters that determine the costs of constructing and later operating a pipeline system for typically decades, optimising such infrastructure is a complex task. It is not only a question of the number of parameters, but also of their mutual dependencies and individual influence on the overall costs. The primary requirement for the design of a pipeline system is the intended transport capacity, that must be achieved at minimum costs for planning, construction (CAPEX) and long-term operation over the entire service life (OPEX), i.e. at minimal levelised costs. The optimal system configuration is a smart balance between the physical key-figures of the constructed infrastructure and the most efficient mode of operation, mainly the pressure range. Key-figures of the system configuration are the optimal pipe diameter and the number, location, and capacity of compressor stations. The most efficient operating mode is inextricably linked to the system configuration of the pipeline system and vice versa. The optimum in terms of minimal levelised costs includes all system parameters of the transmission system.

This article presents a two-step approach for gas pipeline optimisation, applied to hydrogen. In the first step, a simplified spreadsheet calculation is used to approximate the optimal set of system parameters. Finally, in the second step, the optimal system configuration and operating modes are refined and confirmed by detailed model-based simulations using the complete formalism of fluid mechanics and thermodynamics.

Every optimisation process requires a defined target function based on the complete list of optimisation criteria and a solid cost model. The intended transport capacity shall be made available at minimal costs for planning, construction (CAPEX) and long-term operation over the entire service life (OPEX). The parameters to be optimised can be divided into two groups: 'system configuration' on the one hand and 'operational process conditions' on the other. There are many mutual dependencies between the parameters of both groups.

A solid cost model is essential since every change of a technical parameter like diameter, wall thickness, pressure range, compression capacity and alike has significant impact on the total CAPEX and OPEX. This article presents a two-step approach with focus on optimising the diameter and the operational conditions for long-distance transmission pipelines carrying hydrogen.

Qualitatively, it is quite easy to judge the consequences of changing one of the parameters. But quantitatively it is hard to find the optimum in the parameter space without a strictly mathematical optimisation approach. The complexity of the optimisation process is caused by the multiple mutual dependencies between all the parameters of the system configuration and operating conditions. And not all parameters have the same magnitude of impact on the total costs.

Optimisation approach

Basic considerations

One of the main parameters to be optimised is the pipe diameter. Although in principle, the diameter is a continuous variable, in practice it is a discreate parameter due to the available standard sizes of pipes on the market. Also, the number of compressor stations is obviously a discrete parameter. All other system parameters are continuous variables like compression ratio, transmission pressure range etc.

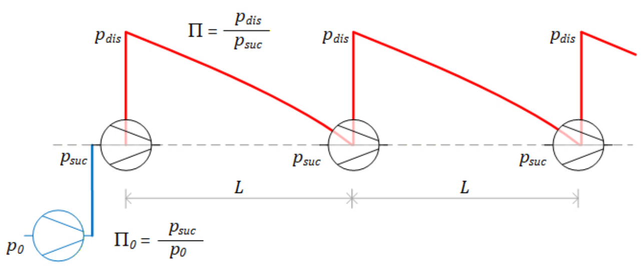

Figure 1. Long-distance pipeline with source pressure lower than minimum transmission pressure.

Table 1. Parameters used in the example calculations		
Maximum flow rate	70 kg/s	← 8.4 GWh/h (LHV = 33.33.kWh/kg)
Maximum operating pressure	100 bar(g)	
Annual utilisation	85%	
Costs of pipeline + stations	See Figure 3	← Linear part of the pipeline system includes pipes and coatings, pig launcher/receiver, block valve stations as well as pipeline construction and commissioning
Costs of one compressor station	58 Mio€ base	
Plus	2.3 Mio€/MW	
Intake pressure	20 bar(g)	
Delivery pressure Step 1: open	Step 2: 30 bar(g)	
Electricity	60 €/MWh	
Efficiency el. compressor drive	96%	
Efficiency of compression	78%	
Additional power of utilities	2.5%	
Service life	25 years	
Annual cost increase	3%	
Maintenance % of CAPEX	2%	
Total pipeline length	2500 km	
Maximum distance btw. CS	500 km	

Operational requirements and boundary conditions of a transmission line are:

- Intake pressure at the first station of the pipeline.
- Minimum and/or maximum delivery pressure at the terminal station of the pipeline.
- Maximum flow rate, i.e. the annual throughput divided by the utilisation factor.

Throughout this article, the maximum flow rate is expressed in terms of mass flow rate in kg/sec., but can also be expressed as norm volume flow rate in m^3/h or transmitted energy per time in GWh/h with e.g. a lower calorific value (LCV) of 33.33 kWh/kg).

System configuration and operational parameters to be optimised are:

- Distance and elevation profile along the pipeline route.
- Internal diameter of the pipe ($D > D_{min}$) and roughness.
- Number, locations and compression capacities of the compressor stations along the pipeline, which implies determination of the minimum pressure level within each pipeline section, not necessarily identical with the delivery pressure.
- Intended service life (typically at least three decades).

The minimum required diameter is a good starting point for the optimisation procedure. It is determined based on the maximum allowable flow velocity to limit erosional issues that could be caused by advection of liquid droplets and solid particles in the gas stream. Flow velocity limits may be requested by the codes and standards to be applied for the particular project:

$$v_{max} \quad \rightarrow \quad D_{min} = \sqrt{\frac{4\,\dot{m}}{\pi\,\rho(p,T)\,v_{max}}}$$

In case of hydrogen, let us assume a maximum acceptable flow velocity of 20 m/sec. Hydrogen at 12°C has a density of approximately $\rho = 4.2$ kg/m^3 at 50 bar(g), the delivery pressure assumed in this example. For a mass flow rate of 70 kg/sec. (8.4 GWh/h), the minimum required internal diameter would be approximately 1030 mm. The next larger standard pipe diameter is 42 in. If the delivery pressure was only 30 bar(g), the pipe diameter would already require slightly more than 48 in. to keep the flow velocity at the delivery point of the pipeline below 20 m/sec. The flow velocity assumes its maximum at the delivery point. Another case: If the maximum flow velocity was 40 m/sec., the minimum diameter at delivery

	CAPEX [Mio€/100km]							OPEX [Mio€/100km] 25 years							Levelized Costs [€/MWh/100km]						
Π	30	40	50	60	70	80	90	30	40	50	60	70	80	90	30	40	50	60	70	80	90
1.1	347.7	254.4	211.3	188.3	174.8	166.5	161.1	808.0	540.0	423.3	366.2	337.0	322.4	316.0	0.739	0.508	0.406	0.355	0.327	0.313	0.305
1.15	286.7	219.5	188.7	172.5	163.2	157.5	154.0	743.1	503.0	399.3	349.4	324.7	312.9	308.4	0.659	0.462	0.376	0.334	0.312	0.301	0.296
1.2	255.4	201.6	177.2	164.4	157.2	152.9	154.0	701.2	479.0	383.8	338.6	316.7	306.8	319.8	0.612	0.435	0.359	0.322	0.303	0.294	0.303
1.25	236.0	190.5	170.0	159.4	153.5	154.3	155.7	669.2	460.7	372.0	330.3	310.6	322.7	337.2	0.579	0.416	0.347	0.313	0.297	0.305	0.315
1.3	222.6	182.8	165.0	155.9	154.4	156.0	157.4	642.6	445.5	362.2	323.5	323.9	339.6	354.1	0.553	0.402	0.337	0.307	0.306	0.317	0.327
1.35	212.7	177.2	161.4	154.3	156.0	157.6	159.0	619.7	432.4	353.7	323.1	340.4	356.1	370.6	0.532	0.390	0.329	0.305	0.318	0.329	0.339
1.4	204.9	172.7	158.5	155.9	157.6	159.2	160.6	599.2	420.7	346.1	339.1	356.4	372.1	386.6	0.514	0.380	0.323	0.317	0.329	0.340	0.350
1.45	198.7	169.2	156.2	157.5	159.1	160.7	162.1	580.7	410.1	339.3	354.7	372.0	387.8	402.2	0.498	0.370	0.317	0.328	0.340	0.351	0.361
1.5	193.5	166.2	157.0	158.9	160.6	162.2	163.6	563.7	400.4	350.6	370.0	387.3	403.0	417.5	0.484	0.362	0.325	0.338	0.350	0.361	0.372
1.55	189.1	163.7	158.5	160.4	162.1	163.7	165.1	548.0	391.4	365.6	384.9	402.2	417.9	432.4	0.471	0.355	0.335	0.349	0.361	0.372	0.382
1.6	185.3	161.5	159.9	161.8	163.5	165.1	166.5	533.4	383.0	380.1	399.5	416.8	432.5	447.0	0.460	0.348	0.345	0.359	0.371	0.382	0.392
1.65	182.0	159.6	161.3	163.2	164.9	166.5	167.9	519.7	375.2	394.4	413.7	431.0	446.8	461.2	0.449	0.342	0.355	0.369	0.381	0.392	0.402
1.7	179.0	160.5	162.7	164.6	166.3	167.9	169.3	507.0	386.2	408.3	427.7	445.0	460.7	475.2	0.439	0.350	0.365	0.379	0.391	0.402	0.412
1.75	176.4	161.9	164.1	166.0	167.7	169.2	170.6	494.9	399.9	422.0	441.4	458.7	474.4	488.9	0.429	0.359	0.375	0.388	0.401	0.412	0.422
1.8	174.0	163.2	165.4	167.3	169.0	170.5	171.9	483.6	413.3	435.4	454.8	472.1	487.8	502.3	0.421	0.369	0.384	0.398	0.410	0.421	0.431
1.85	171.8	164.5	166.7	168.6	170.3	171.8	173.2	472.8	426.5	448.6	467.9	485.2	501.0	515.4	0.412	0.378	0.394	0.407	0.419	0.430	0.440
1.9	169.9	165.8	167.9	169.8	171.5	173.1	174.5	462.7	439.4	461.5	480.9	498.2	513.9	528.4	0.405	0.387	0.403	0.416	0.428	0.439	0.450
1.95	168.1	167.0	169.2	171.1	172.8	174.3	175.7	453.0	452.1	474.2	493.5	510.8	526.6	541.0	0.397	0.396	0.411	0.425	0.437	0.448	0.458
2	166.4	168.2	170.4	172.3	174.0	175.5	177.0	443.8	464.5	486.7	506.0	523.3	539.0	553.5	0.390	0.405	0.420	0.434	0.446	0.457	0.467
2.05	166.9	169.4	171.6	173.5	175.2	176.7	178.2	450.5	476.8	498.9	518.2	535.5	551.3	565.7	0.395	0.413	0.429	0.442	0.455	0.466	0.476
2.1	168.0	170.6	172.8	174.7	176.4	177.9	179.3	462.5	488.8	510.9	530.3	547.6	563.3	577.8	0.403	0.422	0.437	0.451	0.463	0.474	0.484
2.15	169.2	171.8	173.9	175.8	177.5	179.1	180.5	474.4	500.6	522.8	542.1	559.4	575.2	589.6	0.412	0.430	0.446	0.459	0.471	0.482	0.493
2.2	170.3	172.9	175.1	177.0	178.7	180.2	181.7	486.0	512.3	534.4	553.8	571.1	586.8	601.3	0.420	0.438	0.454	0.467	0.480	0.491	0.501
2.25	171.5	174.0	176.2	178.1	179.8	181.4	182.8	497.5	523.8	545.9	565.3	582.6	598.3	612.8	0.428	0.446	0.462	0.475	0.488	0.499	0.509
2.3	172.6	175.2	177.3	179.2	180.9	182.5	183.9	508.8	535.1	557.2	576.6	593.9	609.6	624.1	0.436	0.454	0.470	0.483	0.496	0.507	0.517
2.35	173.7	176.2	178.4	180.3	182.0	183.6	185.0	520.0	546.2	568.4	587.7	605.0	620.7	635.2	0.444	0.462	0.478	0.491	0.503	0.514	0.525
2.4	174.7	177.3	179.5	181.4	183.1	184.6	186.1	530.9	557.2	579.3	598.7	616.0	631.7	646.2	0.451	0.470	0.485	0.499	0.511	0.522	0.532
2.45	175.8	178.4	180.6	182.5	184.2	185.7	187.1	541.8	568.0	590.2	609.5	626.8	642.5	657.0	0.459	0.477	0.493	0.507	0.519	0.530	0.540
2.5	176.9	179.4	181.6	183.5	185.2	186.8	188.2	552.4	578.7	600.8	620.2	637.5	653.2	667.7	0.466	0.485	0.500	0.514	0.526	0.537	0.547

Figure 2. Parameters in the Π-p_{suc}-plane for pinpointing the cost minimum (44 in. diameter).

pressure of 50 bar(g) would be 32 in., and 40 in. at 30 bar(g). These simple examples already show that these two parameters alone – delivery pressure and maximum flow velocity – have a major influence on the overall system design.

For long-distance gas pipelines, an appropriate choice of the transmission pressure range is the second essential parameter in the optimisation procedure. Increasing the transmission pressure can reduce the number of required compressor stations at the expense of increased costs for larger required wall thickness (CAPEX), higher equipment class as well as the required additional compression capacity and thus power consumption (OPEX).

The determination of the optimal diameter is a first goal. Starting at the minimum diameter, it then needs to be analysed whether the next larger pipe sizes would lead to lower total costs to build the pipeline system and operate it over its entire service life.

Simplified optimisation approach – step 1

The aim of this section is to present the technical background and a way to determine the levelised cost per energy transmitted and per distance, here per MWh and 100 km. Compression power is one of the major cost drivers as it is needed during the entire service life, usually at least two to three decades. The specific compression power (w) of a compressor is proportional to the natural logarithm of the compression ratio (Π = discharge pressure divided by suction pressure) and a factor formed by the real-gas compressibility factor (K) multiplied by the absolute temperature (T) averaged over the compression process (indicated by the horizontal line on top, see below). The specific gas constant (R_N) equals atmospheric pressure (p_N) divided by norm density (ρ_N) and norm temperature (T_N). The power consumption of the compressor drive (P_{dr}) is proportional to the specific compression power, the mass flow rate and the inverse efficiencies of the drive and the in general polytropic compression process.

$$w = R_N\,\overline{K(p,T)\,T}\;ln(\Pi) \;\;\rightarrow\;\; P_{dr} = \frac{w\,\dot{m}}{\eta_{dr}\,\eta_{pol}}$$

That means, a compression ratio of e.g. 1.5 would require almost the same power consumption compressing the gas stream from suction pressure 30 bar(g) to discharge pressure 45.5 bar(g) as from 50 bar(g) to 75.5 bar(g), the latter with significantly greater reach (L), i.e. the distance until the next compressor station downstream would be required.

In a long-distance pipeline, the minimum transmission pressure is the suction pressure for the compressor stations as shown on Figure 1. The total power consumption for compression is the sum of the power required to lift the intake pressure (p_0) up to the minimum transmission pressure (p_{suc}) and further up to discharge pressure (p_{dis}), plus the power of all compressor stations further down the line.

Compared to the compression power, the other consumers of electricity like gas coolers and utilities, are small and typically contribute only by a few percent to the total power consumption of the entire pipeline system.

The relationship between the operating pressure range, flow rate, diameter and reach can be expressed as follows:

$$p_{dis}^2 - p_{suc}^2 = \frac{16}{\pi^2}\,R_N\,\frac{\langle K\,T\,\lambda\rangle_L}{D^5}\,\dot{m}^2\,L \;\;\rightarrow\;\; L = \frac{\pi^2}{16}\,\frac{p_{suc}^2\,(\Pi^2 - 1)\,D^5}{\dot{m}^2\,R_N\,\langle K\,T\,\lambda\rangle_L}$$

The dimension-less friction factor (λ) is calculated e.g. after Colebrook-White. The pointed brackets indicate the average over the length (L) of the pipeline section, see Figure 1. The function that yields the total costs per length depends, amongst others, on Π, p_{suc}, and D. These three variables determine the reach of a compressor station and ultimately the required number and capacity of the compressor stations.

It is worth to mention that these two simple formulas are sufficient to create a spreadsheet that can approximately and thus preliminarily localise the costs minimum in the parameter space. Detailed thermodynamic and fluid-dynamic calculations are carried out in a second step to precisely localise the optimum.

Annual cost increase percentages (z) over the years of service life (y) are incorporated by a factor that is to be multiplied by the annual OPEX in the first year of operation. If the cost increases are assumed constant over the years, the factor simplifies to:

$$y \;\rightarrow\; \sum_{n=1}^{y} (1+z)^{n-1} = \frac{(1+z)^y - 1}{z}$$

The formulas presented here, are applied to hydrogen and implemented on a spreadsheet to calculate CAPEX and OPEX per 100 km for the entire service life of the pipeline system. The total costs divided by the total energy transmitted during the entire service life yields the levelised costs per MWh and per 100 km. The calculations were carried out for the parameters and constraints:

For very long pipelines and finally aiming at levelised costs per 100 km, the number of compressor stations may be treated as a floating-point variable, n = 100 km/L. Calculations were carried out for each pair of parameters Π and p_{suc} and for a sequence of standard diameters to find the preliminary optimal diameter for the given conditions (cf. Table 1). Figure 2 shows the results for that diameter with the lowest levelised costs – here 44 in., as shown in Figure 3.

Green coloured cells on the spreadsheet (Figure 2) indicate low costs in the parameter plane and thus potential candidates for the optimum whilst red, orange and yellow cells show non-optimal areas. The white figure indicates the minimum levelised costs. Colourless cells are excluded from the optimisation because for these combinations of suction pressure (or lower transmission pressure) and compression ratio the maximum allowable operating pressure of 100 bar(g) would be exceeded.

With 25 years of service life, as used in this example, OPEX dominates the total costs, driven by power consumption for compression. Longer service life periods would even increase this tendency. From the operating cost perspective, it is advantageous to keep the compression ratio low and at the same time operate the pipeline at high pressure to take advantage of the greater reach.

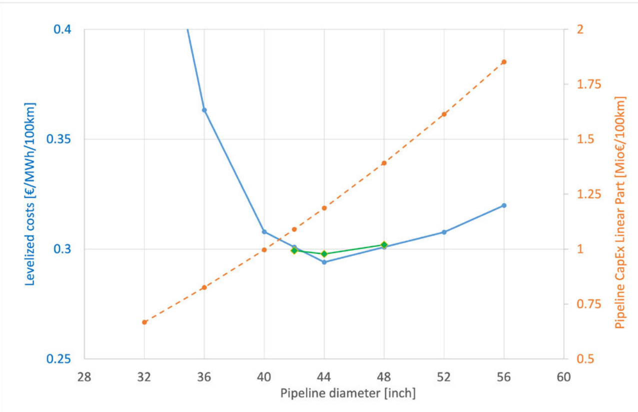

Figure 3. **Optimal diameter 44 in. at cost minimum of approximately 0.29 €/MWh/100 km (green curve, see Step 2).**

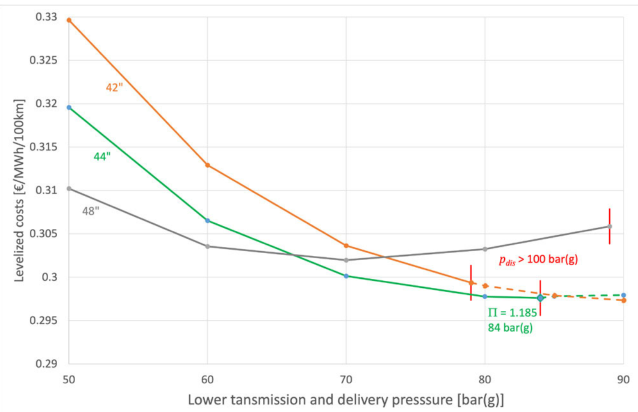

Figure 4. **Double-checking and confirmation of the optimal diameter and operating parameters.**

The absolute minimum of levelised costs found here at 80 bar(g) and Π = 1.2 (44 in.) only indicates the 'neighbourhood' of the optimum in the parameter plane, because:

- The spacings used in compression ratio and lower transmission pressure on the spreadsheet are too wide to localise the absolute optimum precisely.
- For practical reasons, there were some simplifications used in the spreadsheet calculations which are not as accurate as the methods used in Step 2 with complete model-based simulation including detailed fluid mechanics and real-gas thermodynamics.

The concluded optimum diameter of 44 in. and levelised costs of slightly less than 0.3 €/MWh/100 km are therefore only approximate and preliminary at this stage (blue curve on Figure 3).

The impact of the intake pressure on the levelised costs is related to the total length of the pipeline system. Relative to the total costs, the contribution of CAPEX and OPEX to raise the intake pressure up to the lower transmission pressure (or suction pressure) becomes smaller the longer the pipeline system is.

With this approach (Step 1), the delivery pressure for each parameter set is at the same time the lower transmission pressure. Defined boundary conditions regarding delivery pressure are considered in the detailed approach of Step 2.

It is worth to note that the simplified optimisation approach was implemented on a standard spreadsheet tool and that only the three formulas described above were used. The two average values therein were approximated as follows:

$$\overline{K(p,T)\,T} = K(p_{suc},T_{suc})\,T_{suc}\,\frac{1}{2}\left(1+\Pi^{\frac{\kappa-1}{\kappa}}\right)$$

With κ = 1.4 (reciprocating compressors assumed) and a constant average.

$$\langle K\,T\,\lambda\rangle_L = 1.03 \times 288\ \mathrm{K} \times 0.009$$

With this simple spreadsheet calculation tool, the preliminary optimisation can be carried out conveniently. Changing a parameter shows directly the consequences of that measure. The approximate optimal parameter set can be localised very fast. It only needs to be finally double-checked against the complete fluid-dynamic and thermodynamic calculation – see Step 2. The green curve between 42 in. and 48 in. on Figure 3 shows the good matching of results.

Detailed optimisation approach – Step 2

The achievement of the simplified optimisation approach (Step 1) is the convenient determination of the most suitable diameter for the pipeline system and the two operating parameters – suction pressure, which is here identical to the lower transmission pressure, and the compression ratio of the compressor stations along the pipeline – see Figure 1. A detailed model-based calculation (including temperature model, discharge coolers, etc.) confirmed the predictions of the simplified approach Step 1. As shown on Figure 4, also the detailed calculation identifies the 44 in. pipe diameter to be optimal regarding minimum levelised costs.

The 44 in. pipeline is obviously the optimal choice within the given boundary conditions and constraints of this example. The optimal lower transmission pressure at 84 bar(g) yields the minimum levelised costs. With the compression ratio 1.185 the discharge pressure remains slightly below 100 bar(g). If there was no restriction on the maximum operating pressure, a 42 in. pipeline would even lead to slightly lower levelised costs but at correspondingly higher pressure. The 48 in. line has the minimum levelised costs at a lower transmission pressure of 70 bar(g) but above 0.3 €/MWh/100 km.

In real pipeline systems, there are usually additional restrictions and specific requirements that must be considered and complied with. And the number of compressor stations is an integer. Such a requirement is e.g. the minimum and/or maximum delivery pressure that can be lower than the lower transmission pressure as shown on Figure 5. If the delivery pressure is not only an upper limit but shall be met exactly, then at least the last pipeline segment requires a different treatment compared to the other upstream segments.

There are several ways to deal with this constraint:

- Choose the lower transmission pressure equals the delivery pressure (Case A on Figure 6).
- Accept that the excess pressure at the delivery point is simply throttled down to the set point there (Case G on Figure 6).
- Keep the transmission pressure high and reduce the compression ratio only at the last compressor station as sketched on Figure 5 (Case B on Figure 6).
- Cascaded transmission pressure, i.e. reduce the compression ratio at the last and the penultimate compressor stations, and so forth (Case C/D/E/F on Figure 6).
- Apply the distance limitation (here 500 km) only for the last pipeline section and add another station upstream (here 5 x 400 km + 1 x 500 km).

Starting the discussion on the last option: although when adding one compressor station so that all the compressor stations would require less capacity, the levelised costs turn out to be higher than the other presented cases on Figure 6, except for the worst Case A. This leads to the first general conclusion: It is advantageous to utilise the maximum permissible distance between two consecutive compressor stations to keep the number of compressor stations as low as possible.

Case A and Case G on Figure 6 are the two scenarios with 'flat' lower transmission pressure, Case A at 30 bar(g) and Case G at 84 bar(g). Case G is the scenario with minimum levelised costs determined by the simplified approach (Step 1).

Case B – Case F are here called 'cascaded' as they utilise high transmission pressures at pipeline entry and stepwise lower pressure for the line sections toward the end of the pipeline to meet the boundary condition for the delivery pressure there, at 30 bar(g) in this example.

Case A is obviously by far the worst with 35.8% higher levelised costs compared to the best Case F, see the bottom bar on the inserted chart on Figure 6 in comparison to the green coloured bar.

Case B has a lower transmission pressure of 50 bar(g) and a reduced compression ratio only at the last compressor station. Case C has a lower transmission pressure of 60 bar(g) and reduced compression ratios at the last two compressor stations. Case D starts at a lower transmission pressure of 70 bar(g) in the first two pipeline sections and successively steps down to the delivery pressure in the last three sections. The last two cascaded scenarios – Case E and Case F – start at lower transmission pressures of 80 bar(g) and 84 bar(g), respectively. Both scenarios further reduce the levelised costs. Case F is the overall optimum. We cannot go another step up because then the upper pressure constraint (p_{dis} < 100 bar(g)) would be violated.

In a pure transmission pipeline without entry/exit branches underway it would obviously be advantageous to apply a cascaded pressure profile along the pipeline system, like e.g. Case F on Figure 6. However, there may be reasons why such operation would not be suitable. Case C – Case G are all below 0.3€/MWh/100 km; Case D, Case E and Case F are even below 0.29€/MWh/100 km. Thus, there are options close to the overall optimum.

Remark: Case A, with levelised costs of 0.387€/MWh/100km, corresponds to the first column on the spreadsheet, Figure 2. The levelised costs calculated with

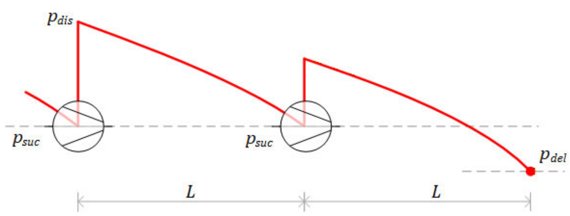

Figure 5. Scenario with delivery pressure lower than transmission pressure.

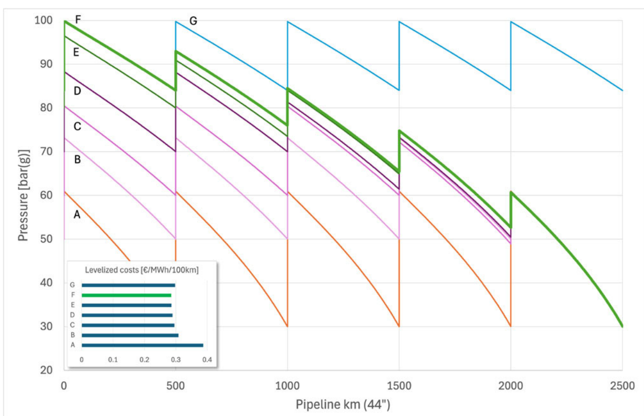

Figure 6. Cascaded vs flat transmission pressure.

the simplified approach at 30 bar(g) and $\Pi = 2$ are 0.390€/MWh/100 km, fully in line with the detailed simulation results. This good agreement is due to the fact that the example model uses a flat elevation profile and a constant ground temperature. The formulas used in the simplified method (Step 1) only represent this situation. Realistic temperature models are typically more complex. Gravity effects in steep sections of the pipeline also lead to deviations from the simple approach, even for the light hydrogen. These details can only be worked out using a full-fledged simulation programme.

Conclusion

Two simple technical formulas plus a factor to take long-term cost increases into account were used to set up the target function for pipeline system optimisation. The simplified optimisation approach was implemented as Step 1 on a standard spreadsheet to calculate the levelised costs for a large number of parameter sets. This spreadsheet enabled us to efficiently narrow down the range in the parameter space in which the optimum is located. Detailed calculations based on a simulation model that takes fluid mechanics and thermodynamics into account were carried out in Step 2 to determine the levelised costs accurately. Compression capacity was calculated with full polytropic approach. Since the approximate location of the optimum was already known from Step 1, only a few of these more complex calculations needed to be done to finally localise the optimum.

Due to the specific conditions that apply to each pipeline system, optimisation is a highly individual task. Real pipeline systems contain more complexity, elevation profiles, no free choice for locations of compressor stations and alike. Such details may cause deviations from the idealised system configuration (as per Step 1) but will not change the main parameters much. Nevertheless, some general conclusions can be drawn.

The simplified approach of Step 1 is efficient and can determine the approximate location of the optimal system configuration in the parameter space very well. It can be used for sensitivity analysis, i.e. to identify those system parameters that need special attention.

The optimal system configuration favours high transmission pressure to take advantage of the greater reach of each compressor station. Only the head compressor station requires high capacity, with higher investment costs for construction and correspondingly higher operating costs. For long-distance pipelines with typical delivery pressure, the lowest levelised costs are achieved when the pressure profile is cascaded from high to low pressure, as shown on Figure 6.

The discussion about the maximum permissible flow velocity appears less critical, as the optimal scenarios result in 30 m/sec. at the delivery point or less at delivery pressure of 30 bar(g).