Techno-economic optimisation of large natural gas transmission systems

by Ansgar Brauer

This article shares experience with the optimal design of large cross-country, onshore natural gas transmission systems. It is essential to find the techno-economic optimum depending on the different design criteria and to keep the balance between market flexibility and minimizing the capital expenditures as main target of the investors. Here the specific gas transportation costs serve as the main benchmark and allow proofing the economic viability of the project. The influence on the specific transportation cost is analysed based on different capacity utilization scenarios applied on a virtual large gas transmission system. For a pipeline system with line pipe diameter 56” and assumed optimal 30 bcm/a capacity the techno-economic optimisation results in specific transportation cost at approximately 3 €/1000 Nm³/100 km. Further it is illustrated how unused pipeline capacity leads to significant higher transportation cost. Due to commercial reasons it is therefore crucial to consider very short build-up phases until the full capacity of the pipeline system is reached. Further parameters with important influence on the specific transportation cost are the amount of capital expenditures, cost of capital and fuel gas cost.

1. FUNDAMENTALS OF NATURAL GAS TRANSPORT THROUGH PIPELINES

Natural gas is transported into the markets by different means:
- via Pipeline (onshore or offshore)
- by vessel as LNG (liquefied natural gas)

The best commercial alternative solution is dependent on project specific circumstances as well as the market conditions. Recently the market has been subject to global impacts such as distance from source to the market, geopolitical framework, exploration of new sources, unconventional such as shale gas. In this paper the focus will be on onshore natural gas pipelines only.

The two main parts of a natural gas transmission system are the compressor station and the pipeline itself. Both have a significant influence on the design (dimensioning) and thus on the cost of a pipeline system. The transport capacity of a pipeline increases disproportionately to an increasing internal diameter. In the same way higher operating pressures by using appropriate compressor stations allow for larger capacities provided that the framing conditions remain the same.

For the transport of natural gas via pipelines over long distances there is a need to build up a pressure difference between the start and the target point. This is to overcome pressure losses due to the expansion of the gas. The necessary pressure increase up to the required operating pressure level needed for natural gas transport is achieved at the starting point of the pipeline system using a head compressor. Additional compression facilities are integrated into the pipeline system by so-called intermediate compressor stations. Their distance among others is dependent on the pipe diameter, operating pressure and length of the pipeline. Depending on the gas volume flow one or more compressor units can be operated in parallel, or in rare cases also in a serial configuration [1].

2. TYPES OF EXPENDITURES

2.1 Operational Expenditures – OPEX

The operating cost for a pipeline system mainly consists of the following items:
- Energy (in particular the fuel gas used for the compressors)
- Maintenance
The operating cost can be divided into fixed and variable OPEX. Fixed OPEX occur independently from the transported volume as an absolute value [€/a] whereas variable OPEX change proportionally with the amount of the transported natural gas volumes. Energy costs, namely fuel gas, apply to the latter type because it is heavily dependent on the throughput.

In international natural gas transmission systems, the fuel gas cost is not seen as relevant for the investors as this part of the OPEX is usually borne by the users of the transportation capacity, the so-called shippers. Therefore it is not an element of the transportation tariff. The fuel gas is procured either by the shippers themselves as “fuel gas in kind” or the transmission system operator (TSO) via a competitive tendering process. In both cases the cost will be passed on to the shippers.

However, in the scenario considered, the specific transportation cost includes the fuel gas cost because it is an essential part of the techno-economic optimisation procedure. This is the main characteristic of the specific transportation cost compared to the pure commercial transportation tariffs (see Section 4).

2.2 Capital Expenditures – CAPEX

For large international gas transmission systems, the total project cost usually consist of the following main components:

- Technical CAPEX (material, construction and engineering services) for
  - Pipeline
  - Stations (e.g. compressors, metering and regulation facilities, etc.)
- FIEX (for international project financing, interest during construction (IdC), etc.)
- Project management and project development

According to Figure 1, the pipeline itself contributes to the total project cost of circa 60%. Additionally, project management and FIEX each contribute to circa 14% of the total project cost.

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The stations, primarily the compressor stations, are responsible for a share of circa 12% related to the total project cost.

Based on the direct or technical CAPEX definition, i.e. the total project cost minus the project management and development cost as well as the FIEX, the cost relation pipeline vs. stations is 84% vs. 16%.

As a ballpark figure for large natural gas transmission systems the material cost of steel line pipes are responsible for up to 35% to 40% of the technical CAPEX.

As steel prices are heavily dependent on the worldwide economic activities and thus are very volatile, they have an influence on the economic calculations in the respective project phase as well as the transportation cost. Figure 2 shows the steel price curve for line pipe made of grade L485MB or X70 as an example of the volatility in the past years.

Considering the long time periods between project development until the final investment decision, it becomes evident that an overly optimistic material cost estimate or forecast may bear a certain risk for the investors. On the other hand worldwide recessions and a decrease of the steel price may allow for reduction in the project budget.

Finally the influence of the steel price on the business case particularly the total project cost is not that decisive as often assessed and intensively discussed. A difference in the unit price in the range of ±100 €/t und ±200 €/t compared to a basic price at 1,000 €/t results in a moderate fluctuation of total project cost of between ±3.3 %
und ±6.5 %. In the present extreme case – refer to Figure 2, years 2009 vs. 2010 showing circa -400 €/t coming from a unit price of more than 1,200 €/t – the delta is less than -12 %.

# 3. OPTIMISATION APPROACH

## 3.1 Principles of optimising the pipeline diameter

Firstly during the optimisation of a pipeline system it should be evaluated which nominal pipe size (NPS) at a given gas flow and a fixed pipeline length serves best in order to minimize the total cost. Here it is mainly differentiated between capital expenditures (CAPEX), operational expenditures (OPEX) and financial expenditures (FIEX).

The calculations during the techno-economic optimisation should be performed latest during the basic engineering phase and should be reflected in the project cost estimate. Normally they should be already part of the system design exercise in the course of the conceptual design or feasibility study and continuously adjusted during the following engineering stages (at least during basic engineering).

Limited by functional and environmental constraints, different pipe sizes could be suitable assuming a constant gas flow and a fixed total system length. Therefore the theoretically suitable standard NPS are determined during the hydraulic calculation of the pipeline. The calculations also consider potential capacity reserves for additional build-up (or ramp-up) volumes which might be follow later during operation. The calculations are performed by considering various flow parameters as well as hydro-dynamic functions valid for the fluid.

The internal diameter of the pipeline as well as the number of the compressor stations and their required power demand are the result of the hydraulic calculations. The higher the compression ratio, i.e. the ratio discharge vs. suction pressure of the compressor, the higher the temperature of the natural gas. The need for implementing gas coolers is determined by the temperature resistance (normally < 40 °C) of the internal flow coating as well as the external coating of the pipeline and especially by the material for the field applied coating protecting the welded joints. The flow coating is a thin epoxy layer applied onto the internal surface of the line pipe. Usually it leads to an improvement of the hydraulic conditions and thus to an increase of the natural gas volumes transported through the pipeline. Based on experience this flow increase can be estimated in the range of 10 % while the technical CAPEX increase by only circa 5 %. Hence the application of flow coating is industry standard for large natural gas transmission systems.

From the economic point of view the decision of the most advantageous NPS has to be taken in line with the following principle:

Assuming a constant gas flow, the CAPEX increases when choosing a larger NPS as the higher investments in the pipeline overcompensate for the concurrent smaller investments in the compressors. In parallel the OPEX decreases with increasing pipe size due to smaller pressure losses along the pipeline length and thus the compressors consume less fuel gas. Adding both functions shows a typical, convex-shaped total cost curve. The minimum of this new function represents the techno-economic optimum related to the chosen framing parameters (Figure 3). Empirical values based on executed projects and multiple net present value (NPV) calculations performed (see Section 3.5) help to reduce the efforts for these complex optimisation calculations and hence keep engineering and project costs within the budget.

The pipe size optimum is substantially influenced by the discount rate assumed during the NPV calculation. Increasing the discount rate a higher operating pressure (which leads to higher OPEX) gets increasingly advantageous compared to enlarging the pipe size (which leads to higher CAPEX / FIEX). In contrast the influence of the energy cost becomes visible as well. With high energy costs, fuel gas savings due to use of large NPS and greater compressor station distances are more favourable than smaller NPS and less distance between the compressor stations.

## 3.2 Case Study

Figure 4 shows an example of such an optimisation result for a virtual new-built natural gas transmission system. It has a starting capacity of 20 bcm/a with a design pressure of 100 barg and a total length of 4000 km. The optimisation calculations have been performed for different possible NPS between 42” and 56”. In addition the distance of the compressor station (CS) has been varied within the 44” pipe size class. High energy costs based on hub prices have been assumed for this example.

From Figure 4 it becomes evident that a 48” pipeline system with a design pressure of 100 barg and a compressor station distance of 250 km which considers no build-ups is the most economical solution in the present case. This is because it shows the smallest NPV. Note that the NPV is always mentioned in this article as a positive sign. At the same time this theoretical case study shows that the economic optimum is relatively shallow close to another viable alternative namely the 44” system with a compressor stations distance of only 167 km. In practice the slight difference in the NPV between these two alternatives would have been compensated due to the inac-
The basic parameters used among others for each of the NPV calculations are summarized in Table 1. These assumptions are also valid for the following cases in the text.

### 3.3 Optimisation potential for larger pipe diameters

Even large gas transmission systems with capacities > 30 bcm/a and NPS beyond 48” can be optimised despite the fact that the maximum internal diameter for steel pipe for gas transport purposes is 56”. For natural gas transportation the use of intermediate NPS such as 50” or 52” is still unusual and not industry practice. This is because the corresponding main fittings such as block valves, pig launcher/receiver, etc. are not supplied regularly on the market. In addition the pipeline contractors do not have the required equipment such as pipe bending machines for these intermediate NPS. Hence no significant cost advantages could be achieved in practice with these intermediate pipe sizes even if it is a long pipeline system with a corresponding high contract value. From today’s point of view in any case the choice will be made between 48” or 56” NPS. The respective pipeline components are available as standard offerings by various competing suppliers.

It has to be noted that in practice the topographical, permitting, legal or other constraints do not allow full compliance with the optimal compressor station distances anyway. Therefore compromises have to always

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**Table 1**: Overview of basic assumptions used for the exemplary NPV calculation in this article in the course of the techno-economic optimisation

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Underlying assumption</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pipeline length</td>
<td>4000 km (cross-country)</td>
</tr>
<tr>
<td>Design pressure</td>
<td>100 barg</td>
</tr>
<tr>
<td>Discount rate</td>
<td>10% p.a.</td>
</tr>
<tr>
<td>Observation period</td>
<td>30 years, thereof 5 years construction and 25 years operation</td>
</tr>
<tr>
<td>Steel price</td>
<td>1000 €/t</td>
</tr>
<tr>
<td>Fuel gas cost</td>
<td>1.8 €-ct/kWh (assumed gas price in the target market)</td>
</tr>
<tr>
<td>Financial expenditures</td>
<td>Mirrored 5% p.a. interest during construction, no project financing</td>
</tr>
<tr>
<td>Reference conditions natural gas</td>
<td>Normal cubic metre (Nm³) – Temperature: 0°C; Pressure: 1.01325 bara</td>
</tr>
<tr>
<td>Further assumptions</td>
<td>■ Medium difficulty factor during construction</td>
</tr>
<tr>
<td></td>
<td>■ No build-ups</td>
</tr>
<tr>
<td></td>
<td>■ No intermediate take-offs</td>
</tr>
<tr>
<td></td>
<td>■ International project financing</td>
</tr>
<tr>
<td></td>
<td>■ Project joint venture abroad</td>
</tr>
</tbody>
</table>

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**Figure 4**: Techno-economic optimisation using a natural gas transmission system as a capacity of 20 bcm/a as an example: Comparison of NPV (expressed as positive sign) for different nominal pipe sizes and compressor station distances.
be made with regard to system design when compared to the ideal solution. In practice this often results in choosing the next higher NPS size.

As a consequence for a 56” pipeline system as optimisation parameters remain only the pressure level (design pressure determines the wall thickness of the steel pipes) and the variation of distance of the compressor stations (assess additional compressor station CAPEX versus fuel gas consumption).

It should be noted that 56” systems are relatively rare in Europe because they require high CAPEX and thus in the beginning lead to high transportation cost if there is idle capacity.

3.4 Effect of the build-up on the techno-economic optimum

If it becomes evident that a stepwise build-up is most likely for the pipeline system, this will result in different kind of optimization problem namely weighing up either two smaller pipelines to be installed one after the other or one bigger pipeline laid directly from the beginning in order to transport the expected build-up volumes. However the latter case is subject to a high pre-investment and plenty of idle capacity in the first years of pipeline operation. This decision is driven by the ratio between pipeline construction cost and pipe material cost (especially the steel price) with regard to the selected NPS. Intermediate build-up steps can be dealt with the addition of compressor in existing stations or the construction of new compressor stations.

Assuming either a slow build-up or an unknown final capacity of the pipeline system depending on the project specific framing conditions and despite higher construction cost due to higher material costs and a greater pressure loss it could be advantageous to build a second pipeline as a part or full loop only when the gas demand really requires this. In this case a high pre-investment would be avoided [2]. The right of way for the required parallel pipeline would have been secured during the permitting process for the first pipeline string.

Implementing part-loops, i.e. parallelising in sections of the existing pipeline between two compressor stations, result in a gain of additional capacity. Adding a parallel pipeline in the same NPS to achieve a capacity increase of 50% would require the length of the loop pipeline to be in the range of 75 %. For natural gas pipeline systems without intermediate take-offs the location of the loops is irrelevant, whereas for pipelines with intermediate take-offs or feed-ins the parallelisation of the section with the greatest specific pressure loss results in the biggest capacity increase [2].

As a rule of thumb such a special approach is recommended to be investigated further if the initial capacity of a natural gas pipeline is expected to double not before the first 10 to 15 years of operation.

3.5 Empirical values ("Rules of Thumb")

Based on empirical values derived from respective NPV calculations the numbers depicted in Figure 5 have been proven as the techno-economic optimal design for natural gas transmission systems in Western Europe. Optimization calculations for large natural gas transmission systems have shown that based on frame conditions in Western Europe a compression ratio, i.e. the ratio discharge vs. inlet pressure of the compressor, between 1.3 and 1.6 correlates with the economic optimum. For a 56", 100 bar system with a capacity of ca. 30 bcm/a and a load factor assumed as 0.9 the optimum corresponds to an average compressor stations distance of circa 250 km. In countries or projects where fuel gas costs are charged.
rather at production costs ("lowest value principle") and if possible including any tax reliefs rather than at hub related market prices, shorter distances for compressor stations (e.g. 100 to 125 km) could be economically viable. Considering a corresponding system design due to the higher operating volume this leads to an increased capacity of the pipeline up to 30 bcm/a for 48" and 46 bcm/a for 56". Taking into account the long life time of the pipeline system this approach results in equal specific transportation costs despite the fact that the CAPEX are higher because the compressor stations are nearly doubled and the OPEX are higher due to an increased fuel gas consumption.

Besides that, in the recent past 120 bar natural gas pipeline systems have been realized. One example is the ca. 1074 km long natural gas pipeline between Bovanenkovo and Ukhta which has been built from 2008 to 2012. It is dedicated to transport Russian natural gas from the Yamal Peninsula towards Western Europe. L555MB or X80 steel pipes in 56" designed for a maximum operating pressure of 118 barg have been used. The average distance of the 9 intermediate compressor stations is circa 120 km [3]. Accordingly the maximum capacity of one pipeline string is ca. 57 bcm/a, whereas the compression ratio is ca 1.5. Predictions regarding the cost-effectiveness of such exceptional 120 bar systems are made in Section 4.1. Due to their uniqueness and the fact that those systems can only be realised in remote areas this article will not deal in depth with such high pressure pipeline systems.

4. SPECIFIC TRANSPORTATION COST AS ECONOMIC CRITERIA

4.1 Empirical values ("Rules of Thumb")

From Figure 6 empirical values for specific transportation cost depending on the NPS can be derived. The figures are based on a techno-economic optimisation for 100 bar natural gas pipeline systems based on Western European quality and price standards. Further the parameters listed in Table 1 have been assumed.

The calculation of specific transportation cost for a 120 bar system made of 56" line pipe (see Section 3.5) shows that in comparison to a 100 bar system no significant advantages can be achieved (approximately 2.4 €/1000 Nm³/100 km versus 2.6 €/1000 Nm³/100 km, refer also Figure 6) if it is based on respective cost assumptions in particular for the fuel gas. In contrast when assuming fuel gas cost at presumable production cost around 0.4 €-ct/kWh [4] the results are in the range of 2.0 €/1000 Nm³/100 km and thus the upside potential related to the specific transportation cost reaches beyond 20%. In this case a 100 bar pipeline system would bring a cost benefit of only 8% (refer to Figure 7).

The empiric values for specific transportation cost shown in Figure 6 are based on the assumption that the capacity limit of each natural gas transmission system is already reached immediately after commissioning. In practice a certain build-up is observed during the period of pipeline operation, therefore sometimes it can take years until the full capacity of the pipeline system is finally used. Analogously less natural gas is transported during the observation period which is one parameter for the calculation of the specific transportation cost which results in a reduction of the NPV sum of the benefit units. This value is depicted as a denominator and part of the transportation cost calculation. However the numerator (NPV sum of the expenditures) does not become smaller. Consequently this results in a larger quotient which is exactly the amount of the specific transportation cost.

The specific transportation costs used in the techno-economic optimization should not be mixed up with the transportation tariff used in so-called tariff model which serves commercial purposes to determine the business case of the entire pipeline project. Hence the transportation tariff will be calculated more detailed while focusing on financial conditions as well, such as country-specific tax and regulatory regimes as well as the risk profile and the specific requirements of the investors. In the present case the specific transportation costs solely serve the techno-economic optimisation of gas transmission systems in the respective engineering phase. For this exercise the approach is accurate enough and the results are generally in the range of the transportation tariff when considering nearly identical main parameters.

4.2 Parameters influencing the specific transportation costs

4.2.1 Modeling a virtual reference system

The following conclusions are based on different calculations for a virtual natural gas transmission system which main parameters are listed in Table 1. The basis for the investment decision for the construction of the pipeline system is a long term gas transportation agreement on a take-or-pay basis valid for 25 years. The contracted optimal capacity is 30 bcm/a without build-up.

As standard or reference system a natural gas transmission system made of line pipes with NPS 56" designed for a maximum pressure of 100 barg is used. Accordingly when taking into account the above mentioned limiting conditions (see Table 1) and other parameters which are not explained in detail here as well, the specific transportation cost for this reference case are at approximately 0.92 €-ct/kWh or 2.6 €/1000 Nm³/100 km (refer also Figure 6).
4.2.2 Sensitivity analysis

In order to verify the impact of different input parameters on the specific transportation cost a sensitivity analysis has been performed by varying the following input parameters individually each:

- Considering of volume build-up with 10 / 20 / 30 bcm/a (in 5 and 10 year steps)
- Total CAPEX decrease or increase by 20% due to changing material and construction costs
- Discount rate has been decreased by 2% down to 8% and increased by 2% up to 12%
- Observation period has been shortened to 15 respectively 20 years of operations (instead of 25 years)

- OPEX: Fuel gas costs have been decreased by 1.4 €-ct/kWh down to 0.4 €-ct/kWh (exemplary production cost [4]) or increase to the level of 2.3 €-ct/kWh

The results of the sensitivity analysis are shown in Figure 7 and are subject to further discussion in the following.

4.2.2.1 Build-up

The results of the sensitivity analysis have shown that especially the length and the approach of the build-up have a significant impact on the amount of the specific transportation cost. Here the cost increase by 33% for the scenario "5 year step" and by 77% for the scenario "10 year step".
“10 year step” compared to the reference case. The reason for this is that the technical CAPEX for pipeline material and construction are normally responsible for approximately 85% of the direct or technical CAPEX of a large natural gas transmission system (refer Figure 1).

The remaining 16% are related to the compressor stations. Hence a huge amount of the CAPEX has to be spent already when starting the project implementation. Therefore in this early stage the specific transportation cost are high due to the lack of available gas volumes to serve as beneficial cost units already from the beginning (see Section 3.4).

Hence the duration and structure of the build-up has a significant impact on the amount of the specific transportation cost. The issue discussed is illustrated in Figure 8. Here the capacity increase is realised by adding single compressor units or new compressor stations into the pipeline system.

This also leads to the conclusion that having only small gas volumes available at the start-up date of the pipeline and an expected long build-up period, the use of already existing gas networks should be taken into account. In this case the transportation costs could be reduced down to an economically viable amount in order to prepare the basis for the project’s business case.

Experiences from the past have shown that sometimes natural gas transmission system are planned and built by means of choosing a NPS which is too large. The optimistic assumptions for the business case that the degree of capacity utilisation will increase continuously with the years and the build-up until the final capacity is reached will be realised quickly then does not become reality.

4.2.2.2 CAPEX

In relation to the CAPEX as a rule of thumb it has been shown based on the underlying assumptions that a 20% CAPEX increase or decrease affects the specific transportation costs by roughly the same percentage (Figure 7).

4.2.2.3 Discount Rate (WACC)

The expectations on the return on invest of the investors or the level of the discount rate, often termed as WACC (weighted average cost of capital), significantly influences the amount of transportation costs. A decrease of 2% points p.a. leads to an decrease of 16% and vice versa an increase of 2% points p.a. leads to an increase of 18% related to the specific transportation costs (Figure 7).

4.2.2.4 Observation Period

Is the observation period and figuratively the amortization period of the project is shortened by 5 years from 25 to 20 years respectively by 10 years from 25 years to 15 years the specific transportation cost will increase by approximately 6% respectively 17% (Figure 7).

4.2.2.5 OPEX: Fuel Gas Cost

For this sensivity analysis the fuel gas costs have been reduced by 1.4 €-ct/kWh down to 0.4 €-ct/kWh in order to exemplary investigate the resulting effects. As shown in Figure 7 this leads to a reduction of the specific transportation cost by circa 8%. However an increase of the...
fuel gas cost by 0.5 €-Ct/kWh up to 2.3 €/Ct-kWh will result in an increase of the specific transportation costs by ca. 2%.

5. CONCLUSION

It has been demonstrated that several technical and project specific as well as commercial parameters influence the techno-economic optimization of an onshore pipeline system for natural gas transportation. Already in the concept study stage when assessing the general technical feasibility of the project the system design by means of hydraulic calculations should be followed by the respective NPV calculations for optimization purposes. Only this will ensure a reliable statement with regard to the specific transportation costs and hence to the economics of the new natural gas transmission system.

From the analyses shown in this article the following conclusions and rules of thumb can be derived:

- The construction of large cross-country pipeline systems with a capacity between 20 and 30 bcm/a requires significant long-term investments. The investment has to be refunded using the income from natural gas transportation over a period of usually 20 years to 25 years. To ensure this sufficient and reliable upstream capacities have to be secured for the pipeline.

- Large pipeline projects need a long development time until the realisation (sometimes 5 to 10 years or more), connected with high project development costs, which could together with the upfront project financing fees sum up to an amount of 30% of the total project cost. The FIEX have to be recovered through the transportation tariff.

- For the economics of large and new natural gas transmission systems it is essential to have only short build-up phases (< 3 to 5 years) and reach the maximum capacity as soon as possible. If this cannot be ensured either the use or expansion of existing gas pipeline systems or the modular and stepwise construction of new transmission systems should be considered to reduce the specific transportation costs. The provision of unused capacity is desirable and often demanded by the market participants but always leads to higher cost.

- As a rule of thumb specific transportation cost around 3 €/1000 Nm³/100 km serve as a benchmark for new-build and fully loaded natural gas transmission systems with capacities beyond 20 bcm/a. However difficult route sections e.g. through high mountains and swampland in combination with idle pipeline capacity can lead to a significant increase of this figure.

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