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ENVIRONMENTAL ASPECTS IN DESIGN AND OPERATION OF LONG- DISTANCE GAS TRANSMISSION SYSTEMS

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1 INTRODUCTION RWE

RWE Energy is the RWE Group's sales & marketing and grid company for Continental Europe. In a total of 12 regions, including six outside Germany, RWE Energy AG offers electricity, gas, water and related services on a one-stop basis. Our customers include households, SMEs, business and industry, municipal utilities and regional suppliers. Within the different regions RWE Energy operates about 100.000 km of distribution and transport pipelines. In some regions gas distribution started more than 100 years ago. Additionally RWE Energy is operating 10 underground gas storage facilities in Germany and the Czech Republic and a peak-shaving LNG-plant in Germany.

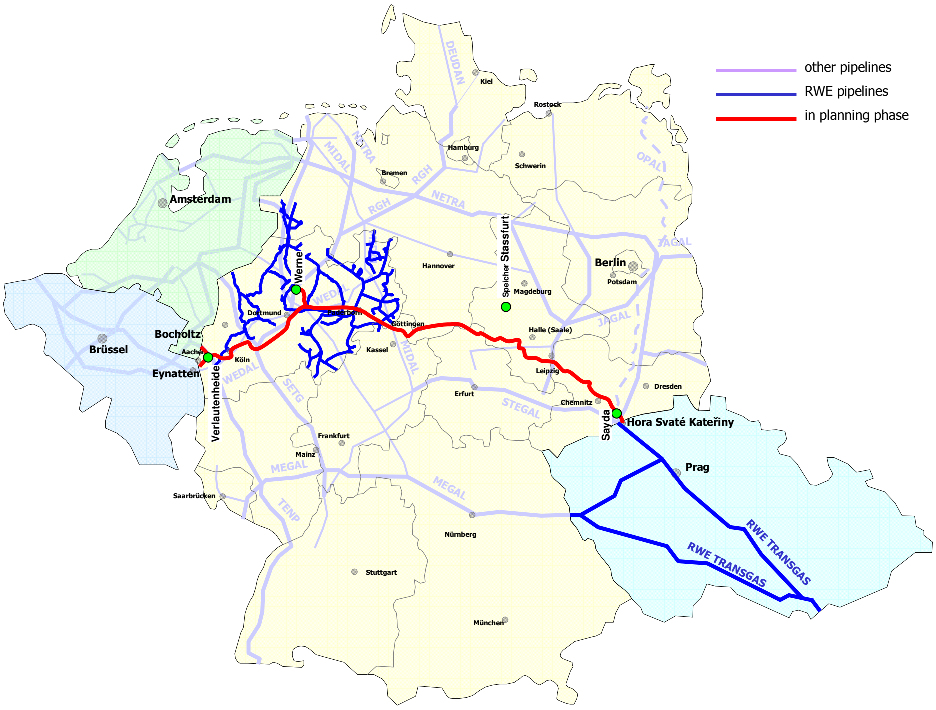


Figure 1: RWE - Gas grid

2 BACKGROUND

The design and operation of modern natural gas transmission systems is a much diversified business both globally and from a project-to-project point of view, while environmental aspects will become a more and more important factor. The countries within the European Union have committed to reduce their CO_2 emissions by 20% up to the year 2020. As an example gas transport system operators within Europe have to buy so-called emission certificates to keep their compressor station operator licence. Therefore environmental considerations also have an increasing impact on the capital and operational expenditures of gas transmission. Naturally there are many aspects with impact on the decision making process. Nevertheless the usual factors in calculating the business case for gas transport systems are still valid and have to be challenged with the environmental considerations.

Carbon dioxide emissions to air (and the emissions of other Green House Gases) are almost exclusively associated with the conversion of energy carriers like natural gas, crude oil, etc.

The Kyoto Protocol defines legally binding targets and timetables for cutting the greenhouse-gas emissions of industrialized countries. Accordingly, from an economic or market perspective, one has to distinguish between a mandatory market and a voluntary market. Typical for both markets is the trade with emission certificates:

- Certified Emission Reduction (CER)
- Emission Reduction Unit (ERU)
- Verified Emission Reduction (VER)

To reach the goals defined in the Kyoto Protocol with least economical costs the following flexible mechanisms were introduced for the mandatory market:

- Clean Development Mechanism (CDM)
- Joint Implementation (JI)
- Emissions trading

The CDM and JI mechanisms specify requirements for projects which create a supply of emission reduction instruments, whilst Emissions Trading allows those instruments to be sold on international markets.

- Projects which are compliant with the requirements of the CDM mechanism generate Certified Emissions Reductions (CERs).
- Projects which are compliant with the requirements of the JI mechanism generate Emissions - Reduction Units (ERUs).The CERs and ERUs can then be sold through Emissions Trading.

Nations and groups of nations can also create local emission reduction schemes which place mandatory CO2 targets on entities within their national boundaries. If the rules of a scheme allow, the obligated entities may be able to cover all or some of any reduction shortfalls by purchasing CERs and ERUs through Emissions Trading. While local emissions reduction schemes have no status under the Kyoto Protocol itself, they play a prominent role in creating the demand for CERs and ERUs, stimulating Emissions Trading and setting a market price for emissions.

3 AIMS

Due to technical, economical and/or legal issues a long-distance gas transmission chain often does not consist of just one transmission-concept. Therefore it has to be examined based upon at least three modes of long-distance natural gas transmission:

- Onshore and offshore pipelines
- Transmission of liquefied natural gas (LNG)
- Transmission of compressed natural gas (CNG)

It is very important to have a clear picture of environmental consequences of using different technologies for the major components of a gas transmission chain. For each transmission chain possible optimisations with regards to environmental aspects and especially CO_2 emissions have to be analysed. Moreover, it is a must to study their impact on the capital and operational expenditures of the transmission chains.

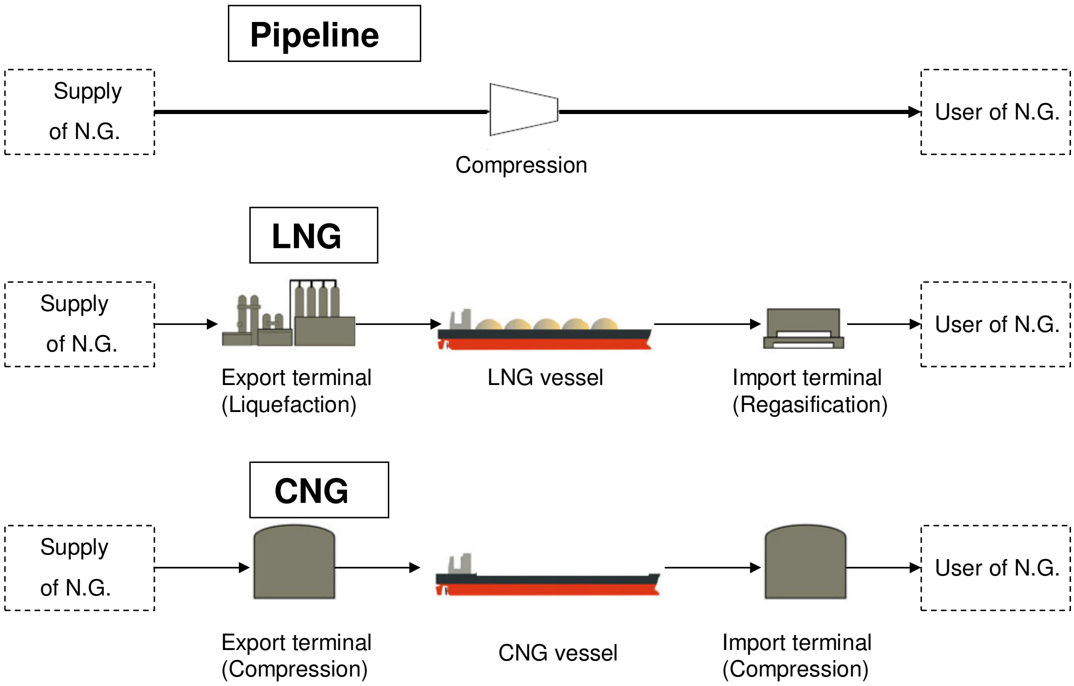


Figure 2: Transmission chains

Several new and state-of-the-art technologies with regard to the pipeline transport of natural gas are available; many engineers are still acting only with "I do it as I did since….". Already some years ago inlined pipes had been introduced in order to reduce friction and thus pressure loss along the pipeline. New materials lifted up the maximum operating pressure of the transport pipeline. Compressor stations came along with low-emission burning chambers of the driving gas turbines. In addition new sophisticated numerical simulation tools supported the design of three-dimensional turbine blades resulting in better efficiencies of the rotating equipment.

The discussion of the differences of design and operation of centrifugal and reciprocating compressors, as well as the options of possible main drivers creates very often new challenges (and profits / added values). Depending on availability of a power line to an existing electricity grid, turbo-type and reciprocating compressors are driven by either electric motors or gas turbines or gas-fired, spark ignited piston engines – (including eventually needed gear-boxes)- or, also very often, by crude oil-fired engines. The selection so far is based, in some degree, on either traditional application for the service type or a clear technological benefit over the other. Residual above ground installations also have to support environmental targets along with the design and operation of the compressor station.

A new interesting option to reduce the loss of natural gas during pipeline-maintenance is the use of evacuation compressors. Evacuation compressors enable the transport system operator to drain specific pipeline sections which have to undergo maintenance procedures without having to blow out the transported gas in that section.

Regarding the environmental aspects of the transmission of liquefied natural gas the new high-tech solutions are sometimes not taken into account. As main components from environmental, as well as from economical point of view, the liquefaction and regasification plants and the LNG vessels have to be accounted for. Today new designed LNG vessels are replacing the formerly steam turbines running on marine diesel and/or boil-off gas. Further concepts lead to the combination of gas turbine with a generator / electric-motor to benefit from a flexible drive enabling variable speed. The impact of using the boil-off gas within the drive instead of re-liquefaction process could be an option of imminent importance.

As a third and new option to transport natural gas is the consideration of CNG transmission chain. Differences in vessel-design as well as different ways of compressing the natural gas have to be discussed in the background of environmental and economical aspects.

3.1 ONSHORE/OFFSHORE PIPELINES

PIPELINE MATERIAL

Selection of line pipe material and specification of welding procedures are extremely important for successful pipeline projects. Pipeline non-destructive testing (NDT) capabilities and procedures are very often an integral component of this design process. There will be no dwelling on any specific selections since the pipe material chosen purely depends on the operating envelope that includes such parameters as type of gas, gas compositions, flow, pressure and temperatures. Important is also to take into account the differences between onshore and subsea pipelines.

Corrosion phenomenon in the gas industry -particularly in pipelines- is a major concern for many operators who normally want an uninterrupted flow of the fluids.

The corrosion and material engineer is normally harassed by many and heckled by those in the industry who work in such functions as operations, process and maintenance. The corrosion engineer has the onerous task of selecting the appropriate materials without sacrificing the fitness of the materials for the service and at the same time not opting for exotic and expensive materials in the name of corrosion resistance.

It should be clearly understood that no single material is a cure for all the ills of corrosion. Corrosion is a complex activity and a judicious approach is necessary when addressing the issue of material selection. It is equally important to note that an expensive and exotic material may not necessarily be the best choice for corrosion resistance. There may be a cheaper material that provides a more economically attractive solution for the corrosion problem.

Figure 3: Pipe mill (courtesy of Europipe) **Figure 4**: Pipeline laying

Corrosion protection often consists of an air-tight protective layer around the pipeline exterior, and also on the inside if the pipeline is to carry corrosive fluids. The exterior protective layer is often fusion bonded epoxy or asphalt, while interior protective layers often consists of plastic liners. Asphalt if often more popular as exterior coating on larger pipelines, as an epoxy layer is quite thin and easily damaged.

From the environmental point of view it is very important to state that all this has a tremendous influence on the friction losses in the pipe and therefore also directly on the needed power of installed compressors (more power > more emissions!).

COMPRESSOR / MAIN DRIVER TECHNOLOGY

Raising engine efficiency and lowering emission levels can significantly reduce environmental load because large diesel and gas engines have a long lifecycle, typically 25 – 50 years.

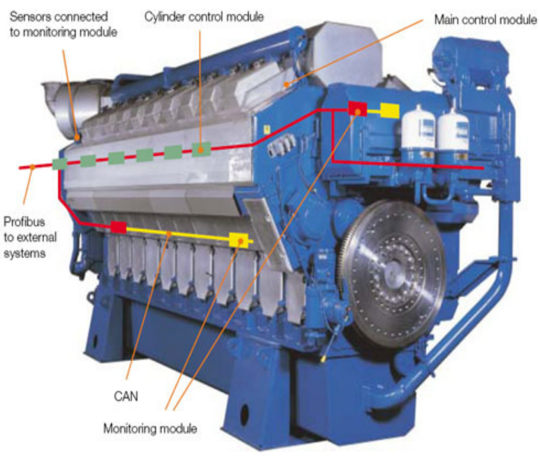


Figure 5: Gas engine (courtesy of WARTSILA)

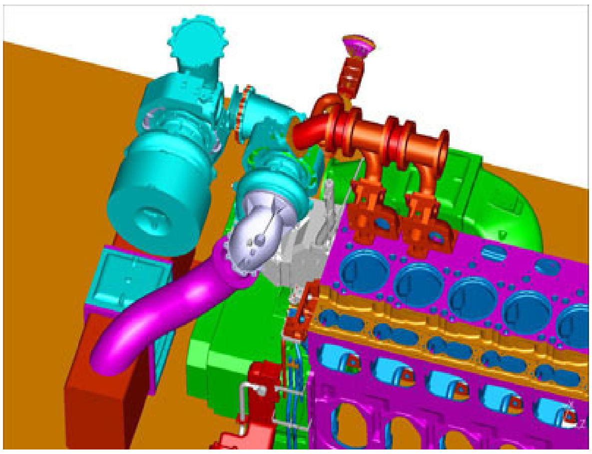


Figure 6: Gas engine (Stress analysis)

The efficiency of an engine is the ratio of the engine's power output to the energy in the fuel fed into the engine. Hence high engine efficiency is fundamental to low fuel consumption and to savings in costs and emissions. Sulphur and carbon dioxide emissions, for example, are directly proportional to fuel consumption and to the content of carbon and sulphur in the fuel.

The shaft efficiency of diesel and gas engines is in the range of 42 – 50% depending on the engine type. Unlike gas turbines, reciprocating internal combustion engines achieve high efficiency over a broad load range. Moreover, their high efficiency and power output remain virtually unchanged over a wide range of intake air temperatures. Compared to a large gas turbine, a multi-engine installation offers the advantage of being able to run at optimal efficiency simply by choosing the right number of engines for the required load.

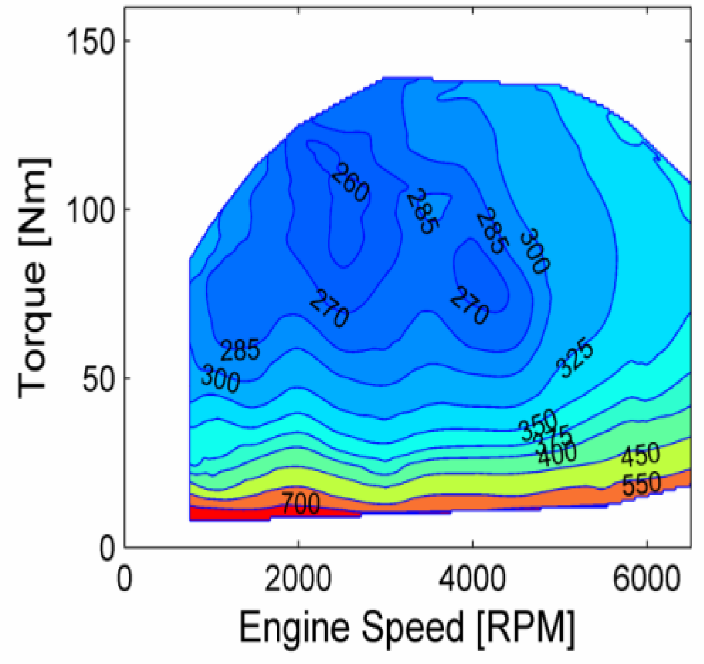


Figure 7: Fuel consumption of gas engines (Torque / Speed)

Engines as main drivers of compressors require very often a steam boiler and steam turbine connected in what is called a “combined cycle”, which can raise the plant’s electrical efficiency to approximately 55%. Another method is to use some of the waste heat from the exhaust gases to produce heat in the form of steam or hot water using a waste gas boiler. This system, called “combined heat and power” (CHP), can raise the plant’s total efficiency to 75 – 90%.

But on the other hand the pace of improvement in efficiency has fallen off somewhat in recent years owing to the increasing restrictions placed on nitrogen oxide emissions.

COMPRESSORS

Reciprocating and centrifugal compressors are basically equal for pipeline duty. For pipeline applications, under steady state conditions, there is a unique relationship between flow through the pipeline and pressure ratio at the compressor station. With increasing flow, the required station pressure increases nonlinearly.

An appropriate selection of aerodynamic stages allows one to perfectly overlay this pipeline characteristic curve with the highest efficiency islands on a centrifugal compressor’s map.

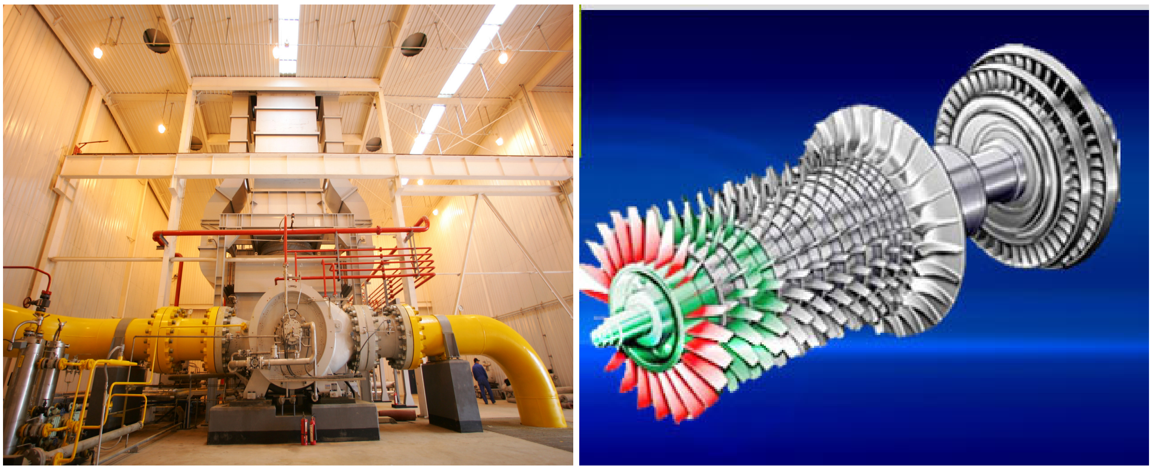


Figure 6: Centrifugal compressors (courtesy of Rolls Royce)

EVACUATION COMPRESSORS

Every now and then there have to be maintenance works at natural gas transport pipelines. For that reason there has to be an expansion of particular parts of the pipe (between two block valves). One option is - and this is still until now in most of the cases the normal procedure - to discharge the gas into the atmosphere. A much better, much more environment-friendly option is the use of so-called evacuation compressors. The compressor unit has to compress gas with decreasing suction pressure (of i.e. >70 bar in the beginning to approx. 1 bar at the end) to a discharge pressure of 70 bar again (at least 1 bar higher than the suction pressure) into another part of the pipe line system. Such compressor units, incl. all auxiliaries (bottles, control systems, filters, scrubbers, etc.) have to be skid-mounted and normally assembled on standardized containers (on trucks) in order to be very movable and flexible.

Figure 7: Evacuation compressor unit on a truck (courtesy of HGC, Hamburg)

3.2 TRANSMISSION OF LIQUIFIED NATURAL GAS (LNG)

State-of-the-art vessels are equipped with slow-speed diesel engines that are more fuel and thermal-efficient than steam turbines with a 30% reduction in overall emissions. Improved economies of scale inherent in the much larger comparative load capacity also are expected to reduce shipping costs by 30%.

New vessels will have many innovative features to maximize cargo deliveries and to ensure the highest levels of safety and reliability, some of which include:

- Membrane type cargo containment system.
- Twin engines and shafts to ensure maximum propulsion safety and reliability, with reduced environmental footprint and twin rudders to ensure safety of navigation and manoeuvrability in confined waters.
- Slow speed diesel engines which are more thermally efficient than steam turbines and therefore burn less fuel, which will produce 30% lower overall emissions compared to traditional existing LNG carriers.
- Cargo re-liquefaction plants will return cargo boil off to the cargo tanks and therefore maximise the cargo delivery at the discharge port.
- Power generation plant has also been enhanced to provide sufficient reserve and thus ensure integrity of supply under all operating circumstances.
- Underwater coatings using the latest technology silicon anti-fouling system, which not only enhances the speed and performance of the vessel, but is also “friendly” to the marine environment since it does not release any biocides into the sea to prevent marine growth on the hull.

Figure 8: LNG-vessel (courtesy of hydrocarbons-technology)

The same trend will continue in the years ahead; to maintain its competitive edge, the engine-makers will need to raise the efficiency of its engines further despite the ever more stringent nitrogen oxide limits.

3.3 TRANSMISSION OF COMPRESSED NATURAL GAS (CNG)

A relatively new idea of long-distance gas transmission is the sea-transport of compressed natural gas (CNG). CNG is produced by compressing natural gas to approx. 1% of its volume at standard atmospheric pressure. Transmission of CNG is carried out in special containers at pressure of up to 250 bar. Compared with LNG, the transmission of CNG is less capital-intensive and thus more appropriate for developing smaller natural gas resources.

On the global market there are different manufacturer of CNG-vessels and CNG-transport containers. Primarily two different transmission methods can be identified:

- CNG-transmission in pipeline-coils
- CNG-transmission in cylindrical steel containers

Figure 9 shows the schematic construction of a pipeline-coil. The CNG is stored in a high pressure pipeline of relatively small diameter which is winded in a spool-like support-structure. The pipeline has lengths of about 10 miles with only a relatively small diameter of approximately 6 inches. Natural gas is stored at pressures around 220 bar at ambient air temperature.

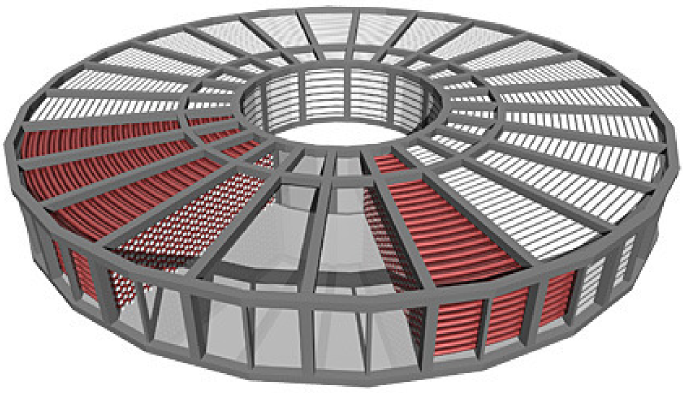


Figure 9: Pipeline-coil (courtesy of SeaNG)

The support-structure is supposed to reduce risk of breakage thus representing an additional protection for the pipeline. Moreover the support-structure allows putting the pipeline-coils together to form stacks which can be placed onto the CNG-vessel. These stacks are configured in different numbers in a series of ship designs offering ship capacities between 50 and 500 MMscf per ship.

Figures 10 and 11 show cylindrical steel containers for CNG-transmission. The CNG can be stored cylindrical steal containers which are either horizontal or vertical tight packed on a vessel.

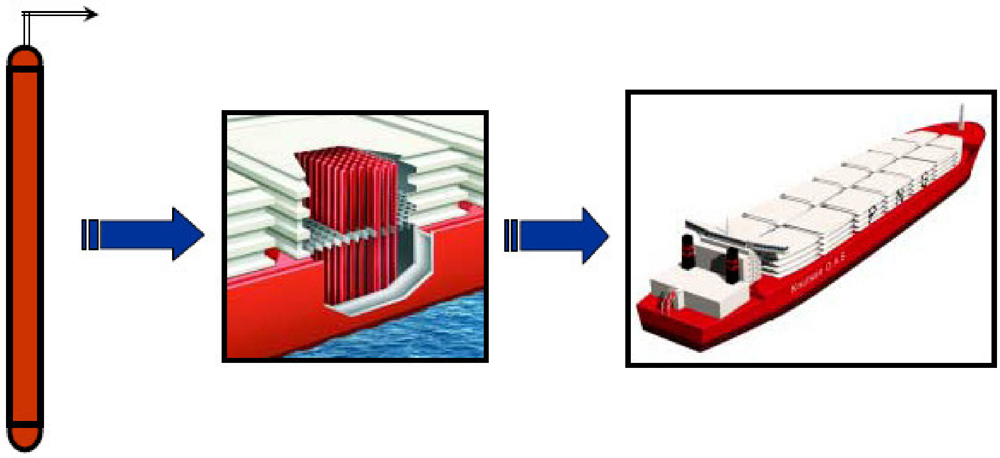


Figure 10: Schematic representation of a CNG steel container and CNG-vessel (courtesy of Knutsen O.A.S. Shipping AS)

The containers are usually made of X80 steel and have diameters of around 1m. Depending on the manufacturer the storage pressure and the storage temperature of the natural gas may vary. A lower storage temperature allows a reduction of the storage pressure which renders the possibility of reducing the containers wall thickness.

Figure 11: CNG steel container (courtesy of TransCanada)

A technical and economical optimum for the CNG-containers and CNG-vessels has to be determined in order to reduce the specific vessel-weight thus reducing the related capital and operational expenditures as well as fuel consumption. This is of special economical interest for a CNG project since the actual CNG-transmission usually is very capital intensive requiring up to 90% of the total capital requirements of the whole CNG value chain.

It has to be mentioned that also the CNG production offers plenty of possibilities to reduce costs and CO_2-emissions. Means of increasing the efficiency of compression are the same as described for pipelines.

4 METHODS AND RESULTS

The crucial point of a gas transmission project is how to transport gas from A to B in the most efficient and economic way. This question is not easily answered because there are many parameters which influence the technical and economic feasibility of a gas transmission project, such as length of the transport route, transport capacity, current steel and energy prices, currency exchange rates, etc. For that reason RWE has developed a calculation tool for estimating all technical and economical variables which are relevant in order to decide on how to transport natural gas in the most efficient way. Important in this context is the calculation of the necessary capital expenditure (CAPEX) and operational expenditure (OPEX) of the project as well as the energy consumption along the transmission chain. Reducing energy consumption is equivalent to reducing CO_2-emmission. Since fuel-costs are one of the main factors of the operational expenditure, reducing energy consumption also contributes to reducing the OPEX of a gas transmission chain.

In order to develop the above mentioned calculating tool different assumptions and simplifications had to be made which were necessary for modelling the CAPEX and OPEX along the gas transmission chains. Specific costs for the main components along the gas transmission chains were estimated based on experience and bibliographical references. A deeper technical consideration of every component and process along the gas transmission chain was neglected because it was neither possible nor necessary for developing a generalised calculation tool. The reason for this is the fact that a detailed calculation is only possible with project specific data which are not existing at the point where the here described calculation tool is intended to be employed.

After identifying the main components of each gas transmission chain given data of similar projects was used in order to determine the CAPEX of these components. The data was gathered from projects which were already realised or where planning or construction was already in progress. Using linear regression a relation between the CAPEX and a characteristic parameter of each component was established. If reasonable the CAPEX were divided into a fixed and a performance-/capacity-specific part. The fixed part represented basic costs which incurred independently from the perform-

ance or capacity of the particular chain-component. In this way so-called economy-of-scale effects were accounted for in the calculation tool.
The projects whose data was gathered in order to determine specific CAPEX for the main components of the gas transmission chains were realised or are going to be realised at different points of time. It was set value on gathering only data from projects whose realisation is not longer than 5 years ago or whose realisation is planned to be in no longer than 5 years from now. Moreover economic data were existent in different currencies (euro and dollar). Because of both above mentioned reasons it was necessary to translate the economic data to a shared level accounting for currency parities as well as inflation. As inflation rate this model employs a rate provided by the European Central Bank averaged for the years 2003 to 2008.

The in such way derived data sets for the CAPEX of gas transmission projects show certain inaccuracies. Reasons are as follows:

- Some of the gathered data are estimations themselves
- For projects where planning is in progress it is not exactly clear under which conditions the estimated CAPEX are valid

The OPEX and the energy consumption of the three considered gas transmission chains and their main components were mainly estimated based on bibliographical references. As far as it is possible the energy consumption of a chain-component was calculated making appropriate simplifying assumptions.

4.1 CALCULATION TOOL

The calculation tool is designed in such way that made assumptions for all relevant technical and economical input data can be adjusted by the user. This allows adjusting the tool to changing technical and/or economical conditions. It especially helps increasing the tool’s sensitivity for changing steel and energy prices which understandably have a huge impact on the CAPEX and OPEX of a gas transmission project.

Figure 12 shows the input data table of the calculation tool:

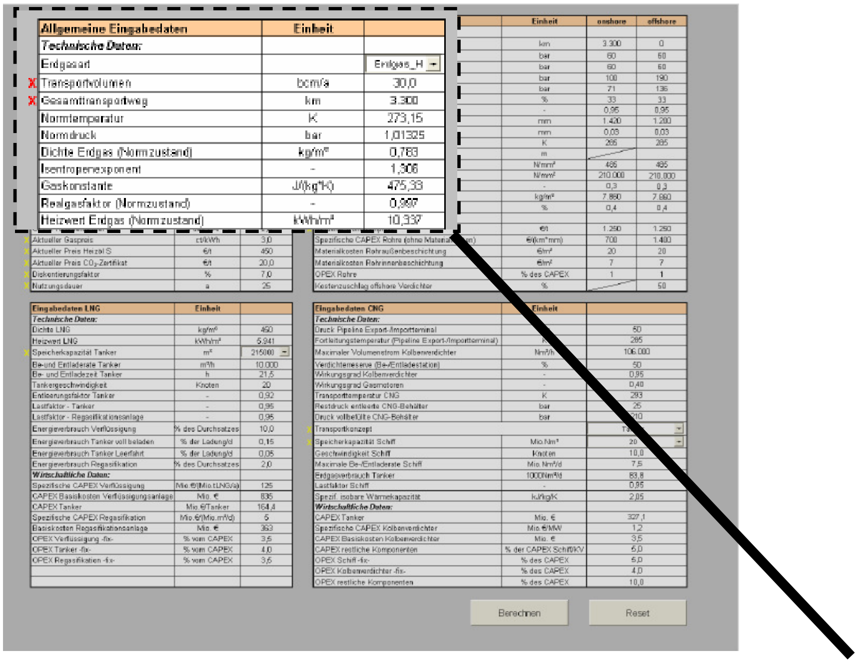
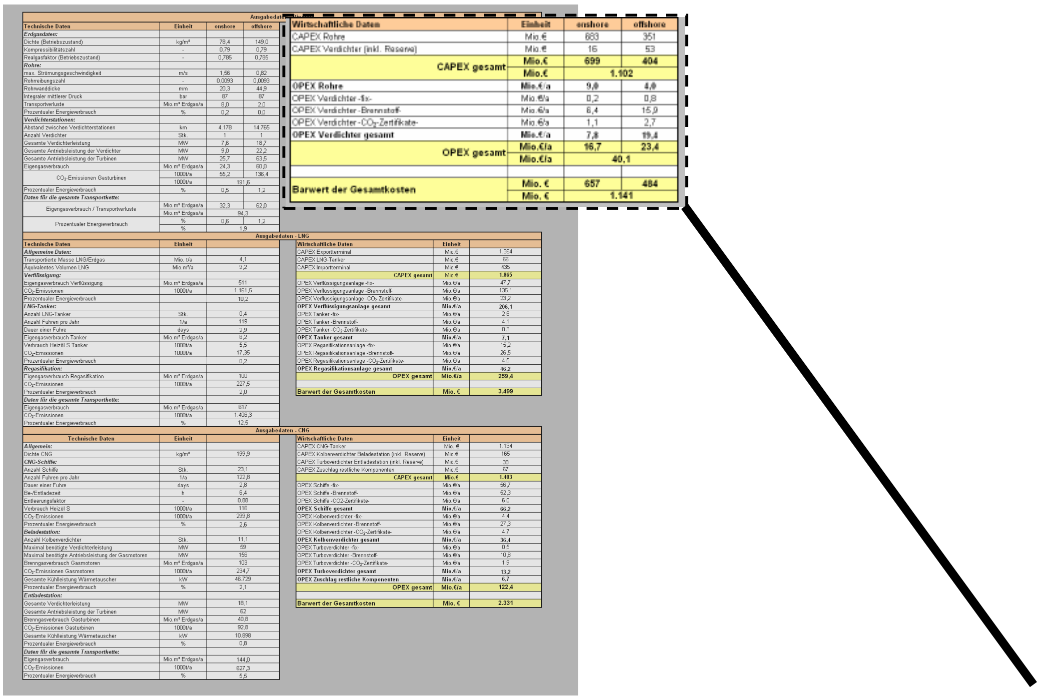


Figure 12: Input data table of the calculation tool

As presented in figure 12 the input data is divided into four different groups (general input data, pipeline data, LNG data, CNG data). Each group is sub-divided into technical and economical input data. The tool also allows choosing between different LNG and CNG vessel-sizes as well as between the option of onshore or offshore pipeline.

After pressing the calculation-button the results of the calculation are shown in an output data table (see figure 13).



Wirtschaftliche Daten	Einheit	onshore	offshore
CAPEX Rohre	Mio €	683	351
CAPEX Verdichter (inkl. Reserve)	Mio €	16	53
CAPEX gesamt	Mio.€	699	404
	Mio.€	1.102	
OPEX Rohre	Mio.€/a	9,0	4,0
OPEX Verdichter -fix-	Mio €/a	0,2	0,8
OPEX Verdichter -Brennstoff-	Mio €/a	6,4	15,9
OPEX Verdichter -CO_2-Zertifikate-	Mio €/a	1,1	2,7
OPEX Verdichter gesamt	Mio.€/a	7,8	19,4
OPEX gesamt	Mio.€/a	16,7	23,4
	Mio.€/a	40,1	
Barwert der Gesamtkosten	Mio. €	657	484
	Mio. €	1.141	

Figure 13: Output data table of the calculation tool

Moreover several diagrams are created which illustrate the essential data of the output data table and help comparing the three investigated methods of gas transmission.

4.2 ADVANTAGES AND WEAKNESSES OF DIFFERENT TRANSMISSION CHAINS

In order to compare the three investigated methods of gas transmission with each other in terms of CAPEX, OPEX and energy consumption, different transmission scenarios are calculated with the tool. The basic scenario is sea-transport of natural gas via offshore pipeline or in form of LNG or CNG.

COMPARISON OF THE COST-RELATED PRESENT VALUE

Five different transport capacities (in the following named $\dot{V}_{gas}$) are chosen and the present values of the transmission infrastructure costs (set together of CAPEX and OPEX) are calculated in dependence on the transport distance (in the following named $l_{transport}$). Figures 14 a) – f) show the results:

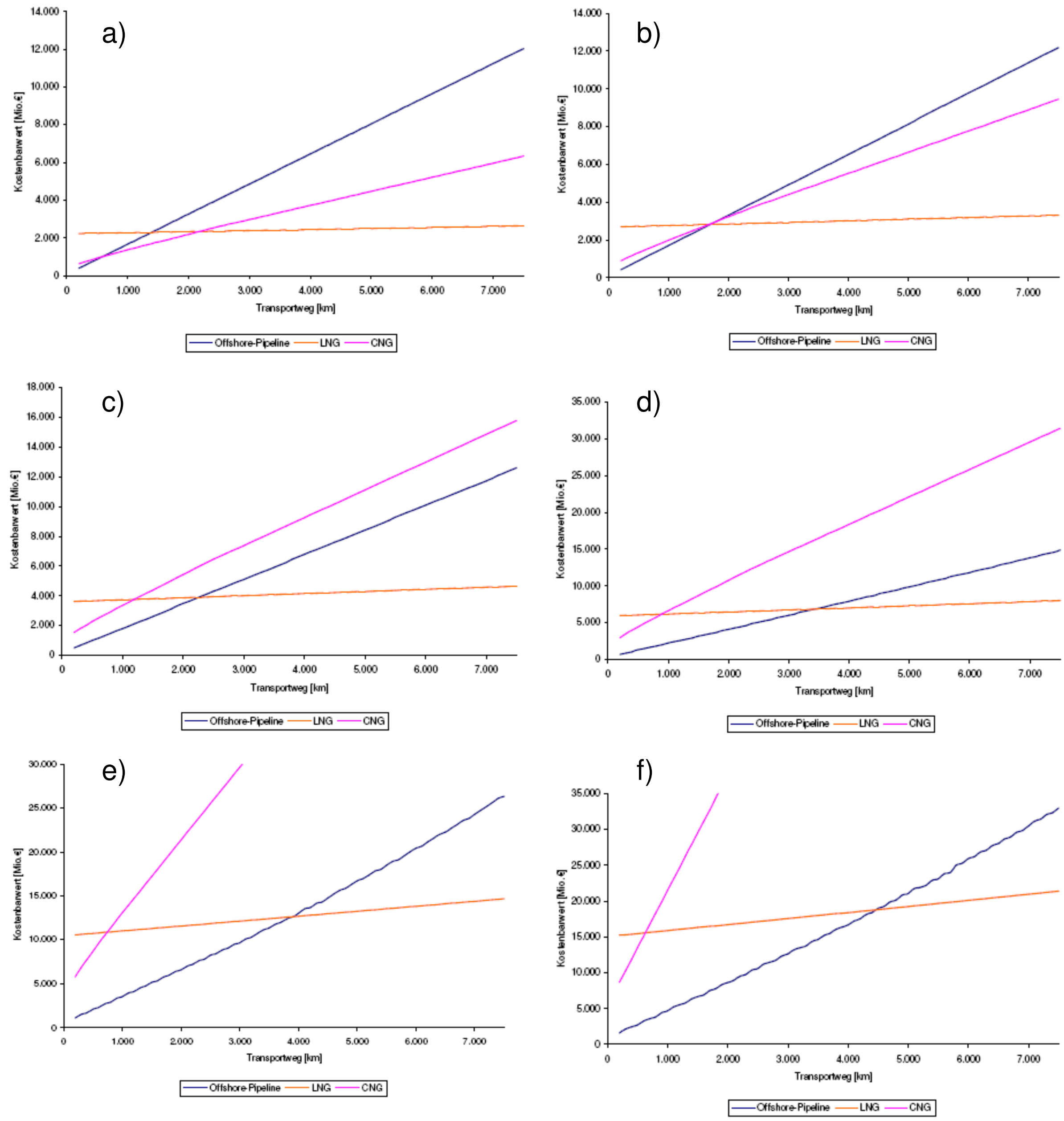


Figure 14 a)-f): Present value of the infrastructure costs for different transport scenarios (a: 2 bcm/a, b:3 bcm/a, c: 5 bcm/a, d: 10 bcm/a, e: 20bcm/a, f: 30 bcm/a)

Figures 14 a)-f) show that the pipeline has an economical advantage over the LNG transport chain at short to medium $l_{transport}$. This can be ascribed to the higher basic investments required for a LNG transmission chain. On the other hand the cost-related present value of the LNG transmission chain increases less fast compared to the pipeline with increasing $l_{transport}$. Thus there is a break-even point of the present value functions of both transmission chains. With increasing $\dot{V}_{gas}$ the break even point is located at larger $l_{transport}$.

Comparing the cost related present value of the CNG transmission chain shows that there is a possible field of application at low $\dot{V}_{gas}$ and short $l_{transport}$. Due to the high dependence of the cost related present value of the CNG transmission chain on the $\dot{V}_{gas}$ as well as the $l_{transport}$, this method of gas transmission becomes quickly uneconomical as soon as one of the mentioned parameters is increased. A closer look at the results of the calculation tool shows that especially the CNG-vessels are a driving factor for the CAPEX and OPEX of the CNG transmission chain.

Figure 15 summarizes the results. The region of stranded gas is plotted qualitatively:

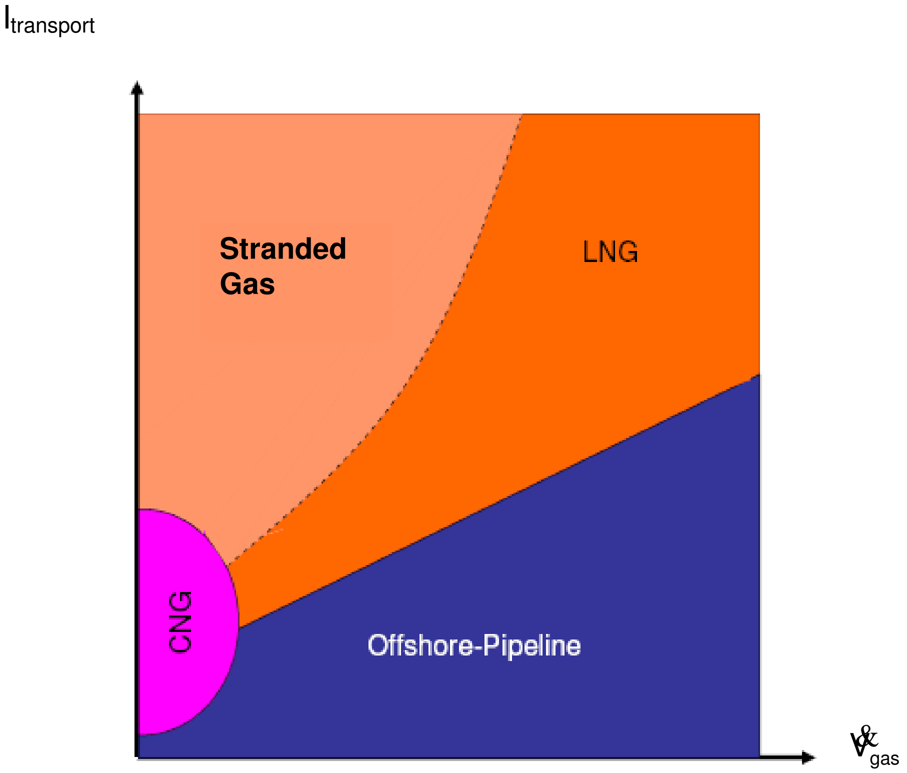


Figure 15: Possible fields of application for the investigated methods of natural gas transmission

COMPARISON OF THE ENERGY CONSUMPTION

Analogous different scenarios of gas transmission projects ($l_{transport}$, $\dot{V}_{gas}$) were selected and the percentaged energy consumption (based on $\dot{V}_{gas}$) along the transmission chain was determined. Following scenarios were chosen:

a) $\dot{V}_{gas}$ = 2 bcm/a ; $l_{transport}$ = 200 km

b) $\dot{V}_{gas}$ = 30 bcm/a ; $l_{transport}$ = 200 km

c) $\dot{V}_{gas}$ = 30 bcm/a ; $l_{transport}$ = 5000 km

d) $\dot{V}_{gas}$ = 2 bcm/a ; $l_{transport}$ = 5000 km

e) $\dot{V}_{gas}$ = 15 bcm/a ; $l_{transport}$ = 2500 km

Figures 16 a) – e) show the results:

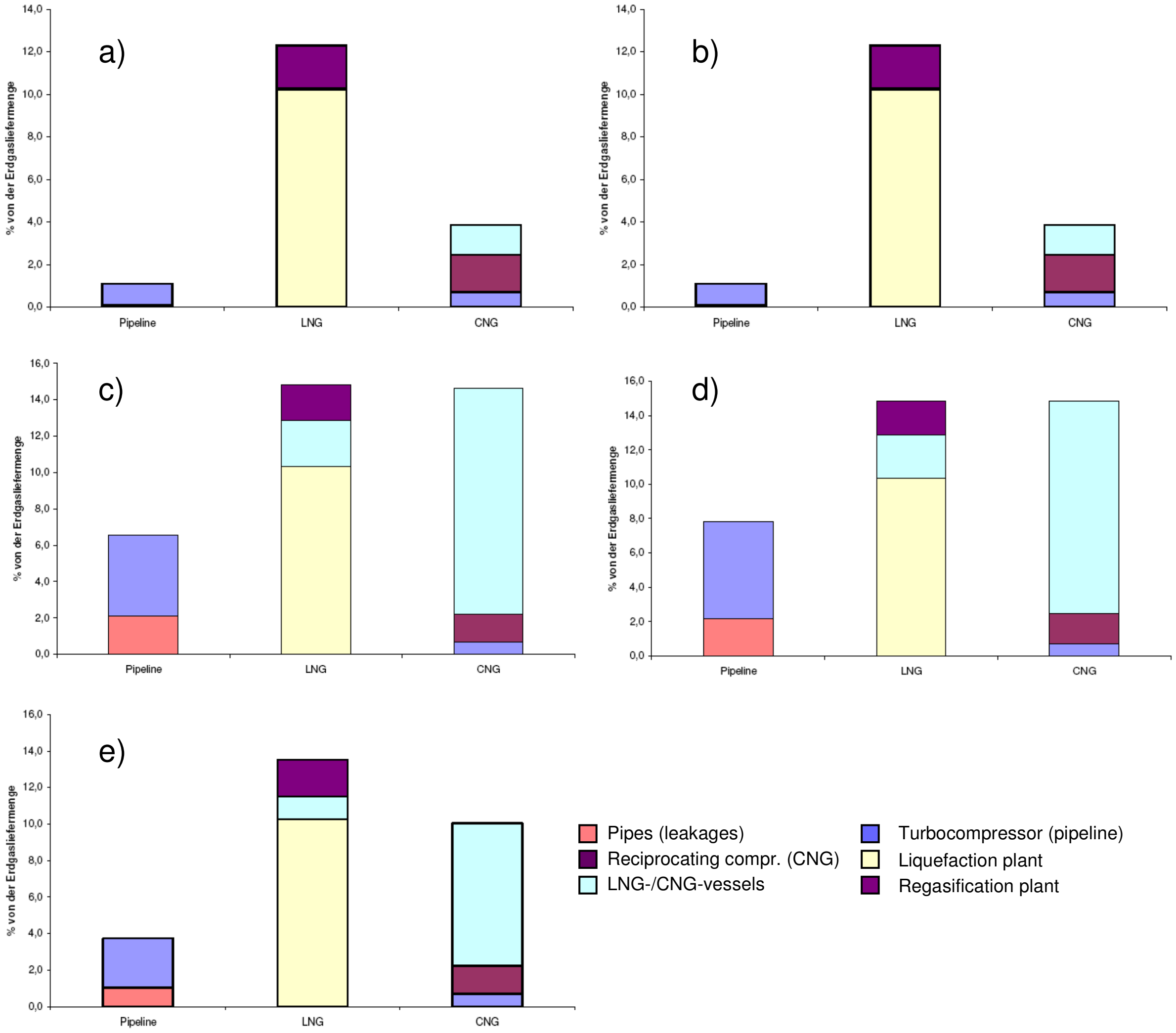


Figure 16 a)-e): Percentaged energy consumption for different transmission scenarios

Figures 16 a)-e) show that natural gas transmission via pipeline is the most energy efficient option. The CNG transmission chain shows a slightly higher percentaged energy consumption when choosing appropriate values for $l_{transport}$ and $\dot{V}_{gas}$. On the other hand the results indicate that the LNG transmission chain has the highest percentaged energy consumption of the three investigated transmission chains. Especially the liquefaction process is highly energy consuming and responsible for the largest part of the overall energy consumption.

3 SUMMARY

Environmental aspects are of growing importance in the designing and operation of long-distance gas transmission systems. Several new and state-of-the-art technologies with regard to gas transmission are available. Gas transmission via pipeline or in form of LNG or CNG has advantages and disadvantages. The improvement with regards to environmental aspects depends strongly on geographical and geopolitical conditions, usage of energy-efficient equipment along the transmission chain. The operation of the different investigated transmission technologies can be optimised by utilization of innovative and state-of-the-art machinery. An optimisation of the combined capital and operational expenditure results in additional environmental advantages.

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