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Vibeke Stærkebye Nørstebø

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Thesis for the degree of
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Optimum operation of gas export systems

Abstract

The world's primary energy needs and consumption are increasing. Fossil fuels are expected to account for around 84% of the overall rise, and natural gas demand will have the fastest growth rate. Natural gas is a fossil fuel which is typically transported through pipelines from production installations to customers. Growing attention is being paid to energy efficiency and environmental emissions in natural gas transport. Operating efficiency is the major way to reduce emissions from system operation, in addition to its impact on system power consumption and operating costs.

The system which is the subject of the analyses in this work is the Norwegian dry gas export system. Exports through this system account for 15% of total European gas consumption, and amounted to 86.2 billion scm in the 2006 gas year. This makes Norway the second largest natural gas exporter to Europe.

Ranked as the world’s largest offshore gas transport network, the Norwegian system comprises 7 800 km of pipelines, gas treatment plants, compressor stations, platforms, exit terminals and crossover legs, and has several gas routing alternatives. The complexity of the system, combined with requirements for energy and environmental efficiency, operational flexibility, capability and availability, and fulfilment of customer demands, make optimum operation of the system challenging. Shippers may vary the nominated gas quantity at exit terminals throughout a day. This makes it hard to forecast exactly how much gas should be delivered and the amount of gas inventory which must be available in the pipeline. Increasing the inventory implies rising the pressure and thereby increased power consumption and environmental emissions from compressor stations. Overall system operating cost is heavily dependent on the operating cost of gas compression. All these aspects demonstrate the need to analyse the integration between system components, and the importance and necessity of clear procedures and models showing how to operate the system in the most efficient way.

The main objective of the work is to establish a model and guidelines for gas export system operation which increase system energy efficiency and reduce environmental emissions while fulfilling customer nominations. The model will also enhance understanding between system and terminal operators, and will be implemented in actual system strategic planning and operation.

Analyses of system operation and integration and development of models are based on actual system operational data and interactions between system elements. Actual performance characteristics of system elements are applied and adjusted to represent actual performance in the models. Theory of systems engineering, operations research and thermodynamics, and software for simulation and statistical analyses are applied as tools in this work.

Analyses have shown that pipeline inventory historically has been too high. A method for finding optimum gas pipeline inventories is established, resulting in recommended inventory curves for the export pipelines. According to the recommended curves, a potential exists for reducing system pipeline inventory by approximately 5% at 70-80% capacity utilisation (average utilisation) in export pipelines. Operational models of the gas export compressor stations in the system are also developed, together with an optimisation model of the whole system. The latter is based on the recommended pipeline inventory curves, the compressor station models and the results from analyses of system integration, constraints and requirements. Operating the system in accordance with the system optimisation model minimises specific power consumption and/or operating costs, and lowers these compared with actual operation. The savings in power consumption and/or operating costs derive from lower intermediate pipeline and compressor discharge pressures, a more equal distribution of gas flow between compressors and pipelines, often having more compressors in operation, and permitting flexibility between the system compressor stations. A validation process, cost-benefit analysis and sensitivity analysis of the model are performed.

In addition, operational guidelines based on the model are established. These are currently under implementation in actual system strategic planning and operation. Applying the established models and guidelines has proved to provide savings in costs, power consumption and emissions, while fulfilling customer demand. The savings adds up to an annual value of almost 2 millions. The annual emission reduction by minimising power consumption for this system utilisation will typically be 0.2 Mscm CO_2 and 2.5 tonnes of NO_X.

The major contributions of this work are presented in six papers contained in the appendices.

Acknowledgements

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First, I would like to thank my main supervisor, Professor Lars Eirik Bakken at the NTNU, for his advice and support. His engagement and good humour, combined with professional accomplishements, have been very motivating and helpful.

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My gratitude also goes to my family, who have supported me throughout the work and have never failed to believe in me.

Trondheim, september 2008

Vibeke Stærkebye Nørstebø

List of publications

The thesis is based on the following publications. These were written, reviewed and presented at international conferences and in journals during the doctoral work (except for the NTNU report).

I. Nørstebø, V.S., Bakken, L.E., and Dahl, H.J, 2006, “Optimum Pipeline Inventory”, Paper No. IPC2006-10285, Proc. ASME International Pipeline Conference 2006, CA-Calgary, Alberta.

II. Nørstebø, V.S., Bakken, L.E., and Dahl, H.J, 2007, “Optimum Operation of Export Compressors”, Paper No. GT2007-27367, Proc. ASME Turbo Expo 2007, CA-Montreal, Québec.

III. Nørstebø, V.S., Bakken, L.E., and Dahl, H.J, 2007, “Energy Efficient Operation of Gas Export Systems”, SPE Journal of Projects, Facilities & Construction, Autumn 2008.
Presented at the SPE International Petroleum Technology Conference 2007, UAE-Dubai. Paper No. IPTC 11280, Proc. IPTC.

IV. Nørstebø, V.S., 2008, “Application of systems engineering and information models to optimize operation of gas export systems”, Journal of Systems Engineering, Autumn 2008, Published Online on May 27 2008.

V. Nørstebø, V.S., 2008, “Application of systems engineering to optimize sustainable performance of gas export systems”, Paper No. 131, Proc. INCOSE Symposium 2008, NL-Amsterdam.

VI. Nørstebø, V.S., Paulsen, E.A., Bakken, L.E., and Dahl, H.J, 2008, “Optimum Operation of gas export system - model validation”, Paper No. IPC2008-64080, Proc. ASME International Pipeline Conference 2008, CA-Calgary, Alberta.

Nørstebø, V.S., 2004, “Liberalisation of the European gas market”, Report No. 2007-001, NTNU (Norwegian University of Science and Technology), NO-Trondheim.

The author’s contribution

Several people have contributed to these studies and are aknowledged in previous chapter. The following clarifies the main contributions of the papers’ main author - the thesis author.

The author of the thesis has:

- performed all the analyses of data in the work
- developed the methods and models for operation of the system and its element
- analysed and validated the established model
- written the main part of the papers
- presented all the papers at international conferences.

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Nomenclature

Symbols

A	Cross sectional area	[m^2]
$a_i - e_i$	Constants, $i = \{1 \ldots 4\}$	[-]
c	Acoustic Wavespeed,	[m/s]
$Cost$	Operating costs	[EUR]
D	Diameter	[m]
E_{CO2}	CO_2 emission rate	[scm/s]
E_{NOX}	NO_X emission rate	[g/s]
$e_{NOX, c}$	Proportionality constants for E_{NOX}	[g/scm]
ex_i	Exponent of performance coefficients (constants), $i = \{1 \ldots 2\}$	[-]
f	Friction factor	[-]
F_f	Friction force	[N]
F_g	Gravity force	[N]
F_p	Pressure force	[N]
$Fuel$	Fuel consumption	[scm/s]
g	Gravity	[m/s^2]
I	Pipeline inventory	[Mscm]
k	Pipeline flow constant	[Mscm/(d*bar)]
L	Pipeline length	[m]
$\dot{m}$	Mass flow	[kg/s]
MW	Molecular weight	[kg/kmol]
N	Number of compressors	[-]
P	Power	[MW]
p	Pressure	[bar]
Q	Flow	[Mscm/d]
R	Gas constant	[J/(kg*K)]
R_0	Universal gas constant	[J/(kmol*K)]
Re	Reynolds number	[-]
S	Compressor speed	[rpm]
T	Temperature	[K]

t	Emission tax rate	[EUR/scm CO2 or EUR/kg NOX]
V	Volume	[m^3]
v	Gas velocity	[m/s]
Z	Compressibility factor	[-]
γ	Specific power consumption	[Wh/scm]
ε	Wall roughness	[m]
ρ	Density	[kg/m^3]
τ_0	Shear stress	[N/m^2]
φ	Flow coefficient	[-]
ψ	Power coefficient	[-]
ω	Pressure coefficient	[-]

Subscripts

c	Compressor
d	Discharge
el	Electrical
i	Inlet
max	Maximum
min	Minimum
$pipe$	Pipeline
rec	Recommended
std	Standard conditions
tot	Total

Abbreviations

BC	Statpipe booster compressor
CBA	Cost-benefit analysis
CO_2	Carbon-dioxide
d	Day
DTSO	Downstream transport system operators
EM	Electric motor
EP	Export pipeline
ET	Exit terminal
EUR	Euro
FU	Gas Supply Committee (Forsyningsutvalget)
GCV	Gross calorific value
GFU	Gas Negotiating Committee (Gassforhandlingsutvalget)
GT	Gas turbine

IEA	International Energy Agency
IP	Intermediate pipeline
KKT	Karush-Kuhn-Tucker
MF	Ministry of Finance
MPE	Ministry of Petroleum and Energy
NCS	Norwegian continental shelf
NDGES	Norwegian dry gas export system
NO_X	Nitrogen-oxides
NP	Node platform
OR	Operations research
P	Production platform
PT	Processing terminal
scm	Standard cubic metre
SE	Systems engineering
SFT	Norwegian Pollution Control Authority
SGC	Statpipe sales gas compressor
TSP	Technical service providers
WI	Wobb index
WTP	Willingness to pay
ÅSG	Åsgard sales gas compressor

1 Introduction

1.1 Background

1.1.1 Motivation

According to the International Energy Agency (IEA) [37], the world's primary energy needs are projected to grow by 55% between 2005 and 2030. Fossils fuel are expected to account for around 84% of the overall rise, and natural gas demand will have the fastest growth rate. In 2005, world natural gas consumption was approximately 2 900 billion scm[1] and European natural gas consumption was 570 billion scm. This corresponds to 24% and 22% of total world and European primary energy consumption respectively. The main uses of natural gas are as a fuel in industry and households, for electricity and heat production, as a feedstock for the petrochemical industry and as a transport fuel. For gas exporters, meeting sales gas commitments is important. Failure to do so would result in gas sale losses and hurting the reputation of the gas exporters.

While energy demand is projected to grow substantially over the coming decades, great concern has been expressed about the rapid increases in anthropogenic carbon- dioxide (CO_2) and nitrogen- oxide (NO_X) emissions from fossil- fuel burning. Global energy-related CO_2 emissions are expected to rise by 57% between 2005 and 2030. [37] The growth in atmospheric CO_2 concentrations is expected to contribute to higher global temperatures and to changes in climate, while local fauna are vulnerable to NO_X emissions.

Natural gas is a clean and high quality fuel. It generates less CO_2 than any other fossil fuels on a per calorie basis. Methane is the main component of natural gas, and its high hydrogen-to-carbon ratio makes natural gas the most environment-friendly fossil fuel available today. From the perspective of environmental protection, natural gas is a good substitute for oil and coal. Nevertheless, a continuous challenge for natural gas exports is the conflict between the need for low-cost supplies of environmentally preferred natural gas and more stringent environmental requirements.

Greater attention is being paid to energy efficiency and environmental emissions in gas export, both nationally and internationally. Operating efficiency is the major way to reduce emissions, in addition to its impact on system operating costs. A gas export system consists of treatment plants, compressor stations, pipelines and exit terminals. For the system operator, optimum integration of pipeline and compressor station operation, flow distribution in the system and customer nominations is of vital importance. Operational experience indicates a substantial need to analyse the integration between these system components and the effects on optimum operation,

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1) standard cubic metre, defined as the volume under standard conditions, i.e. a temperature of 15 °C and a pressure of 1.01325 bar.

deterioration of equipment, energy efficiency and environmental emissions in order to secure the flexibility, capability and availability of the gas export system.

Technology to deal with the aspects discussed above needs to be developed. In response to these aspects, this study aims to obtain insights into the optimum future operation of gas export systems. Oliver's [61] definition of the term "optimum" is applied in this work and defined as follows: the best or most favourable degree, quantity or number. (In optimum operation, technical, environmental and economic aspects are all considered.) Particular attention is given to power consumption. Reducing compressor power consumption is one action which will cut environmental emissions, as well as system operating costs. For gas-turbine-driven compressors, reducing power leads to immediate emission cuts. Where compressors are electrically driven, the result is reduced electricity consumption. Since burning fossil fuels is a common way worldwide to produce energy, reductions in electricity consumption are also important for cutting emissions. Huge costs are associated with the operation of gas export systems. Even a small relative reduction in such costs may provide a large absolute saving.

The system used as the subject for the analyses in this work is the Norwegian dry gas export system.

1.1.2 Norwegian natural gas export

Norway is the third largest gas exporter in the world, and the and the second largest to Europe. Dry gas exports from the Norwegian continental shelf (NCS) account for some 15% of total European gas consumption, and totalled 86.7 billion scm in the 2007 gas year. This corresponds to 16% of total primary energy supply from Norway. [36] The value of the country's petroleum (crude oil, condensate and natural gas) exports was approximately EUR 60 billion, and natural gas accounted for 32% of this export value. In 2007, the petroleum sector accounted for 48% of the value of Norway's exports, and for 24% of value creation in Norway. According to Gassco, annual exports from the NCS over the next 7 - 12 years could reach 120 billion scm. Figure 1–1 shows Norwegian natural gas exports by recipient country. Domestic consumption of natural gas accounts for 0.3% of total Norwegian gas production. [50]

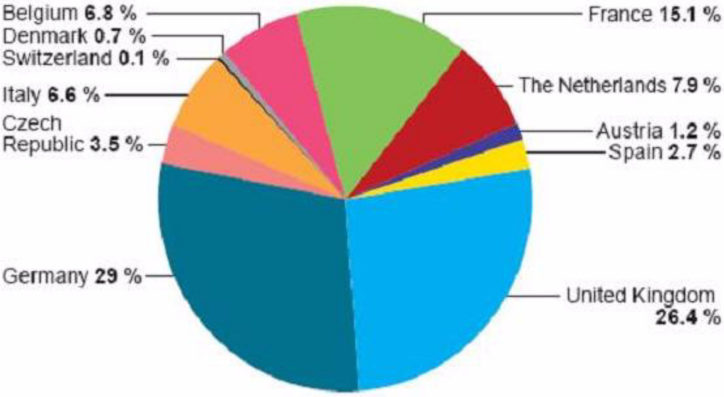


Figure 1–1: Norwegian natural gas exports 2007 by country. Total 86.7 bn scm [50].

1.1.3 Environmental challenges in Norwegian gas industry

The petroleum industry is responsible for 29% of Norway's CO_2 emissions [49]. White Paper no 38 (2003-2004) [48] states that Norway has ambitious goals for overcoming environmental challenges in the industry. Norway's role as a large energy producer will be combined with a role as a pioneer in the environmental field. The Ministry of Petroleum and Energy (MPE) [49] has said that as a consequence of more energy-efficient operation, a realistic and ambitious goal for possible CO_2 emission reduction from the NCS is in the order of 5-10% by 2020. Furthermore, Norway should accept responsibility for reducing global emissions by 20% of national emissions in 1990. The system should strive to achieve these reductions, although they are not specified in any requirements. The Norwegian Pollution Control Authority (SFT) has set mandatory emissions ceilings for gas treatment plants and platforms related to Norwegian gas export. In addition, operators of plants and platforms have an obligation to reduce emissions to the extent possible at a reasonable cost, and to maintain continuous evaluation of actions which can be implemented to increase the energy efficiency of their facilities. [52, 57] The Norwegian government has also introduced taxes on CO_2 and NO_X emissions.

1.1.4 Norwegian gas export system

The Norwegian gas transport network comprises 7 800 km of pipelines and is the world's largest offshore network of its kind. Figure 1–2 shows its scope. Pipelines on the NCS are up to 1 200 km long and can be operated under very high pressures of up to 210 bar. Combined with low ambient temperatures, this provides the opportunity to store up to about 150 Mscm of gas in the pipelines.

Upstream of the export pipelines, gas treatment plants process and compress the export gas and deliver it into the pipelines. There are few compressor stations along the way. Overall operating cost in the gas export system is heavily dependent on the operating cost of gas compressors at the treatment plants. Centrifugal compressors represent one of the commonest ways of compressing natural gas. These are driven by gas turbines or electric motors. According to Wu [77], gas-turbine-driven compressor stations generally consume 3-5% of the transported gas in a network.

The raw natural gas is taken from production wells on the seabed. A topside processing plant compresses the rich gas for transport to the land-based terminal, where the gas is separated in its various components. Quality and volume are measured, and the dry gas is compressed for export via the pipelines. Figures 5–1 and 5–2 provide principle drawings of the export compressor stations at the Troll Kollsnes and Kårstø gas treatment plants respectively.

Shippers may vary nominated deliveries for quantity and exit terminals. Exit point re-nominations must take place a minimum of two hours before they become effective, providing the changes can be accommodated within technical and operational constraints. [26] This makes it hard to forecast exactly how much gas should need to be delivered at the exit terminals, and consequently to plan the amount of inventory which must be available in the pipeline. Meeting sales gas commitments is extremely important. Failure to do so would result in gas sale losses, as well as reducing regularity and hurting the reputation of the gas shippers. This challenges optimum operation procedures in the export system and confirms the importance of maintaining its performance and availability and responding to business and events in a real-time manner.

1.2 History of the Norwegian natural gas industry

The *Ocean Viking* drilling rig discovered substantial amounts of oil on the NCS in late 1969. A few months later, this field was confirmed as large and commercial, and named Ekofisk. Frigg was discovered in May 1971, and ranked at the time as one of the largest offshore gas fields. Gas from Frigg and Ekofisk was sold through contracts from 1973. These were field depletion contracts, under which the total reserves in the field were sold. Norwegian gas exports started in 1977, when the dry gas pipeline from Ekofisk to Emden in Germany was completed. Shortly afterwards, the pipeline from Frigg to St Fergus in the United Kingdom became operational. The next large agreement was signed in 1981 and included gas from Statfjord, Heimdal and Gullfaks. These deliveries started in the mid-1980s. Then came the Troll agreements in 1986. These were volume contracts as opposed to the field depletion contract model. The field of origin for the gas was not specified in these deals. Deliveries from Troll started in the mid 1990s. [3]

The Gas Negotiating Committee (GFU) was established in 1986 and comprised Norwegian companies Statoil, Hydro and Saga. The GFU was responsible for preparing and conducting all negotiations for the sale of Norwegian gas up to the signing of the contract. In 1993, the Gas Supply Committee (FU) was established. This also included foreign companies and was an advisory group for the MPE. The FU dealt with questions related to the development and exploitation of fields and pipelines and the allocation of signed contracts to individual fields. This remained the way Norwegian gas sales were structured until 2001. Gas transport from the NCS was organised in various joint ventures. This meant that different pipelines had different sets of owners, each organised as a separate partnership. [3]

A reorganisation of Norwegian oil and gas activities began in 2001. Gassco was founded on 14 May 2001, and took over as operator of the gas transport system on 1 January 2002. According to the company [29], its responsibilities can be split into three roles:

- Operatorship - Gassco is responsible for operating the Norwegian gas transport system on behalf of joint ventures/companies (owners).
- Developing the gas transport system - Gassco is responsible for taking the initiative on and coordinating the future development of pipelines and transport-related facilities such as process plants and receiving terminals.
- Allocating capacity in the infrastructure - Gassco allocates capacity available at any given time in the pipelines and transport-related facilities.

With effect from 1 January 2003, virtually all the pipelines which previously had different sets of owners were integrated in a major new joint venture called Gassled. This is a joint venture between oil and gas companies on the NCS, and the formal owner of the Norwegian gas transport network.

The GFU was permanently terminated on 1 January 2002, and the oil and gas companies now sell their gas on an individual basis. Each company is free to choose the level of its own sales and to conclude gas contracts with buyers within the limits specified in the production permits issued by the MPE for each field. Two possibilities exist. Either the companies sell gas to transmission companies, or they sell directly to customers. [3]

1.3 Scope of work

The Norwegian gas export system is large and complex, which makes it challenging to achieve optimum operation. It is important and necessary with clear procedures and new and better models showing how to operate the system in the most efficient way. This will be accomplished in this work.

This work has been initiated by Gassco as the operator of the Norwegian gas export system. It expects that operating costs, power consumption and environmental emissions related to system pipeline inventory can be reduced by finding the optimum pipeline inventory levels, establishing guidelines for operating in accordance with these and increasing understanding between system and terminal operators.

The main objective of this work is therefore to:

> *Establish a model and guidelines on gas export system operation which increases system energy efficiency and reduces environmental emissions while fulfilling customer nominations (demand), and which will be implemented in actual system strategic planning and operation.*

The main objective is broken down into the following goals:

A. Develop models which provide a clear and total overview of the gas export system, its structure, interactions and requirements, and then establish a systematic method for pursuing the main objective.

B. Establish a method to predict optimum pipeline inventory which reduces inventory operating costs while providing sufficient operational flexibility, and analyse the consequences by operating in accordance with its recommendations.

C. Establish a model for optimum operation of compressor stations in the export system which increases energy and environmental efficiency by reducing specific power consumption.

D. Establish a model for technically and economically optimum operation of a gas export system which reduces system specific power consumption and environmental emissions, while providing sufficient operational flexibility and fulfilling customer nominations. Results obtained by running the model will be validated and compared with actual system operation.

E. Perform a cost-benefit analysis of gas export system operation in accordance with the established optimisation models, including a sensitivity analysis of variations in key variables and parameters for system operation. Following the analyses and validation from item D, the desire is to implement operational guidelines based on the established models in actual gas export system operation.

In the following work and in the conclusions, the terms main problem and sub-problems are employed synonymously with main objective and goals respectively, in accordance with systems engineering definitions.

1.4 Limitations

The work is limited by the following issues:

- Only existing equipment in the gas export system is taken into account. New designs (processes or equipment) are not considered.
- Restrictions in system operation model with regard to gas blending and gas quality are not included.
- The gas export system's impact on the oil production system is not considered.

1.5 Thesis outline

The thesis gives the background for the papers, summarises their results, and provides some further research.

Chapter 1 introduces the subject and background of the thesis, and defines its scope of work.

Chapter 2 presents a review of relevant works and the theoretical foundation of this work.

Chapter 3 describes the established methodology on how to address and solve the main objective of this work.

Chapter 4 determines recommendations for export pipeline inventory levels.

Chapter 5 determines optimisation models for compressor station operation.

Chapter 6 establishes a model for optimum operation of a gas export system.

Chapter 7 presents validation of the established models against actual system performance and actual operation.

Chapter 8 performs a cost-benefit analysis of operating in accordance with the established model(s).

Chapter 9 discusses implementation of results in actual operation and presents some visual and descriptive guidelines relevant for implementation.

Chapter 10 provides conclusions and recommendations.

Appendix A contains **Paper I**. This paper reports the findings on optimum export pipeline inventory.

Appendix B contains **Paper II**. This paper reports the findings on optimum compressor station operation.

Appendix C contains **Paper III**. This paper reports the findings on energy efficient operation (eller optimum) of gas export systems.

Appendix D contains **Paper IV**. This paper reports on the application of systems engineering and information models to optimise operation of gas export systems.

Appendix E contains **Paper V**. This paper reports on the application of systems engineering to optimise sustainable performance of gas export systems and presents aspects regarding a cost-benefit analysis of gas export system operation.

Appendix F contains **Paper VI**. This paper reports on validation of the models for gas export system operation.

Appendix G presents pipeline inventory and gas flow equations.

Appendix H presents routines and procedures related to booking of capacity, gas transport and communication between the shippers and the gas export system operator (Gassco).

The analyses, opinions, and conclusions expressed in this work are entirely those of the author and should not be interpreted as reflecting the views or positions of the supporting organizations and institutions.

Figure 1–2: The transport network on the NCS [50].

2 Literature review

The purpose of this chapter is to provide an overview of major fields and related works connected with optimum operation of gas export systems which are relevant to this study. Furthermore, approaches taken in this work are discussed in relation to the referenced work. An overview of the theoretical foundation of this work is also provided.

2.1 Status of recent research

Many researchers have analysed and modelled the operation of gas export systems and established methods for optimising such systems or individual system elements. Mathematical modelling is a common tool used in design, operation, optimisation and simulation studies of gas export systems. In accordance with the scope of work and the system of interest in this study, the essence of the literature is presented in this chapter and in the papers. The major fields related to optimum operation of the Norwegian gas export system and relevant for this study are found to be:

- operation of the Norwegian gas export system
- gas export system optimisation
- compressor station operation and optimisation
- cost benefit analysis in the energy and environmental field.

2.1.1 Operation of the Norwegian gas export system

Paper IV (Appendix D) presents relevant studies related to operation of the Norwegian gas export system. Dahl [21] has explored the regulatory regime applicable to this system and how to align system operation with this regime and its requirements. The study relates to the system of interest in 2000.

Operating procedures and guidelines related to technical and economic aspects of gas exports for this system are described in booking, shipping and operating manuals from the system operator, and in operating manuals at the operators of specific terminals in the system. The relevant principles are described in Appendix H. These principles are applied in modelling actual system performance.

Tomasgard et al [72] have established a tool for analysing and evaluating optimum supply structure in the Norwegian gas transport system - GassOptTKL. The model generates a supply strategy which takes into account demand for gas quality and quantity at exit terminals. The main objective of the model is finding optimum supply strategy by maximising throughput (based on total production rate) or minimising the use of energy needed for transporting gas (i.e. minimising pipeline pressures), by taking into account gas blending, system flow distribution and pressure drop in pipelines. The work presented in this thesis focuses more on energy efficiency. Therefore, other aspects, such as compressor station operation and recommended inventory levels, are more emphasised in the modelling in this work compared to the work by Tomasgard et al.

2.1.2 Gas export system optimisation

In addition to the research work by Tomasgard et al, the major literature concerning optimum operation of gas export systems relevant for this work is presented in Papers I and III (appendices A and C). Mathematical modelling is the common tool used in optimisation and simulation studies of gas export system operation. Krishnaswami et al [43] offer an extensive review of many of the studies relating to mathematical techniques for simulating and optimising the operation of compressors and pipelines.

2.1.3 Compressor station operation and optimisation

The major literature concerning the operation of compressor stations is presented in Paper II (appendix B). This review covers various methods for optimising compressor operation, parallel operation of compressors in a station, effects of compressor deterioration, and simulation of compressor station dynamics. Wright et al [76] present an extensive review of the algorithms and numerical models most widely used in compressor and pipeline optimisation.

2.1.4 Cost-benefit analysis

Some research work has been done on cost-benefit analysis (CBA) for natural gas export systems in general. The literature study in this work focuses mainly on how to find the right values for environmental and energy costs and benefits by changing the operation of the natural gas export system.

Godec et al [31] and [32] state that one of the most important issues confronting the natural gas industry is satisfying the potential for incremental future environmental requirements at the same time as natural gas is being promoted as an environmentally preferable fuel. They also state that these requirements are highly uncertain where the gas industry is concerned, both in their potential impacts and in the timing of such effects. The studies conclude that the potential future cost of environmental compliance by the gas industry could be significant, and that air pollution requirements are likely to impose the greatest burden. A methodology which identifies and characterises potential future environmental requirements and their impact on the gas industry is developed.

Regnier [68] studies the volatility of oil, natural gas and energy prices. The results show that prices related to petroleum products are more volatile than for most other commodities (which are often more highly processed), and that the volatility of electricity price is increasing. Furthermore, the volatility of petroleum and energy is important in part because of demand is so high.

Based on this work and a review of studies on emission and energy pricing, attention in the cost-benefit analysis for gas export operation is concentrated on the price and cost of emissions and energy. The major literature related to this topic is presented in Paper VI (appendix F). Some additional relevant literature is presented in the following.

Godahl and Holtsmark [30] study greenhouse gas taxation and the distribution of costs and benefits, with special focus on Norway. They state that, in general, when an emission source is subject to taxation, the cheapest way to adapt this source to the tax is to abate emissions which have a marginal abatement cost lower than the tax. The size of efficiency gains from moving towards a cost-effective regulation scheme depends on the costs of reducing emissions from the various sources and the initial tax level for each source. They also find that Norwegian emission taxes on green house gases have focused on CO_2, with many other emissions exempted from the tax scheme. The way different emissions are taxed will affect the distribution of emission costs in the specific industry or company. This may affect operation of the specific facility. Efforts to reduce costs may not reduce all emissions, but only the emissions subject to high taxes.

Andersen [1] analyses the use of economic instruments in environmental policy. He states that emission tax rates are not determined to match the true environmental costs or to meet specific environmental targets, and are generally much too low. Several other studies on the topic confirm these observations (see Paper VI). Some reasons for this are that many emission-related costs exist, they are often spread and they are difficult to quantify. Andersen further notes that conventional economic theory, calls for the emission tax to reflect the external costs imposed on third parties. Most of the present emission taxes cover only rather local external costs. Externalities at the regional or global level are difficult to quantify. Even more disputed is the valuation of externalities imposed on future generations, such as climate change. Even if these intertemporal externalities are simply neglected, and an accurate estimate of externalities at the regional or global level is made, it would imply much higher emission taxes than present rates.

One other reason for the difficulty of valuing the environment is that estimates of environmental values should incorporate both the option price (for leisure activities, for instance) and existence value. Two relevant aspects of environmental costs are presented in the following sections - those related to water quality and to air pollution.

The value of water and water quality

Fresh water is a necessity and butis becoming increasingly scarce. Several researchers have studied household willingness-to-pay (WTP) for water quality improvements for various purposes, and have estimated the cost of water for different purposes (such as hydropower generation and industrial processing). A review of this work is given in [6]. Emissions may also affect activities related to water, such as fishing, boating and swimming, which must also be incorporated in emission costs.

The cost of air pollution

In general, air pollution incurs in both health and non-health costs. According to Boardman et al [6], health costs include the cost of premature death and of illness. Non-health costs include direct environmental costs, such as those associated with global warming, rising sea levels, coastal erosion, river floods, deforestation, retarded plant growth and reduced agricultural output, and others such as corrosion to buildings, cars and materials as well as loss of scenery. A widely used approach to estimating the cost of pollution is called the dose response function. It relates unit increases in a pollutant to various health effects. These effects are then weighted by monetary valuations of the impacts, usually based on estimates of WTP. This approach excludes non-health costs. Boardman et al [6] present a review of research work using this approach and a summary of the main results. McCubbin and Delucchi [46], for instance, find the health costs of CO_X emissions to lie within a range of about EUR 8-75 per tonne (this equals EUR 0.015-0.140/scm CO_2), and the health costs of NO_X emissions to lie within approximately EUR 950-14550 per tonne (this equals EUR 0.95-14.55/kg NO_X). The gap between the upper and lower limit is relatively large, which confirms the large uncertainty associated with environmental costs. McCubbin and Delucchi [46] point out that the upper-boundary estimate of the value of the life applied in estimating the costs is much lower than some values reported and assumed in literature and studies relating to health effects. Consequently, McCubbin and Delucchi [46] argue that this treatment of uncertainty is conservative.

The Minnesota Public Utilities Commission undertook a review of the costs of air pollution, focusing on environmental costs only (presented in Boardman et al [6]). These costs should be added to health costs in order to approximate the total pollution cost. The review found the environmental costs of CO_2 emissions to lie within a range of roughly EUR 0.23-2.39 per tonne (EUR 0.0004-0.0065/scm CO_2). The environmental costs of NO_X emissions were found to lie within a range of about EUR 14-78/tonne in rural areas and EUR 290-750/tonne in urban settings. (EUR 0.014-0.078/kg NO_X and EUR 0.29-0.75/kg NO_X respectively.) According to Boardman et al [6], these calculations of environmental costs are likely to underestimate non-health costs because they do not include damage to buildings, loss of views and so forth. However, they are much lower than the estimated health costs from emissions.

2.2 Discussion of this work versus previous research

Although a rich literature exists which relates to optimum operation of gas export systems both in general and for specific regions, limited research has been done into optimum operation of the gas export system on the NCS in particular. Since results from this work will be implemented in strategic planning and operation of an actual gas export system, it is important that the models developed represent actual performance of the specific system. Therefore, characteristics of the specific system and system operation have to be taken into account when developing models and guidelines on optimum operation of the system. The Norwegian gas export system differs from most other gas export system in three major ways - long pipelines, high pressure and few booster (compressor) stations along the way. Long pipelines combined with high pressure provide a unique opportunity to store a relatively large volume of gas in the pipelines. Export compressors in the system are driven both by gas turbines and electric motors. The latter are powered from the regular Norwegian grid, which is based mainly on hydropower. The turbines are fuelled directly from the process, before the gas enters the export compressors and pipelines. Furthermore, most references to optimum operation of compressor stations in a gas export system model the compressor as a black box, and few optimisation models include compressor load maps, compressor drivers and polluting emissions from the compressor stations.

The following list shows how different factors are combined in an unique manner in this work compared with the referenced studies.

- The work is based on, and analyses the Norwegian dry gas export system and operation of this specific system in 2007.
- The models are based on the properties, relationships, performance curves and operational procedures of the actual gas export system's and system elements.
- Special attention is paid to the performance and operation of system compressor stations as the prime movers of gas in the network, and to the gas export pipelines.
- General equations and characteristics for compressor performance, pipeline flow and inventory are tuned in such a way that they represent the performance of the system in question, with tuning accomplished by using actual historical operational data combined with regression.
- The model takes into account the fact that forecasts for (future) customer nominations are not exact and certain but can be varied throughout the day, by ensuring a certain pipeline inventory.
- By ensuring a certain pipeline inventory, the model also takes into account the possibility of unexpected shutdowns.
- Special attention is paid to the additional flexibility provided by the opportunity to alternate compressors and use crossover legs between export pipelines in the system.
- Optimisation of system operation considers financial, environmental, regulatory and physical constraints and requirements.
- The work focuses on operational modifications of an existing gas export system (rather than the development of new systems or system elements).
- The emphasis is mainly on optimum operation (rather than specifying existing operation), and related mainly to the physical components (rather than business opportunities and regulatory regime).
- A combination of collection and statistical analysis of operational data, regression analysis, parameter tuning, compressor and pipeline simulation, and linear and non-linear mathematical programming and optimisation is applied in model development.
- Models and guidelines will be developed with a focus on enhancing understanding between different system and subsystem operators.
- Special attention is paid to developing solutions which can be transformed into visual and descriptive operating guidelines for implementation and use in actual operation.

In the CBA performed in this work cost calculations are based on the current emission tax rates and a representative Norwegian average electricity price (which are EUR 0.1/scm for CO_2, EUR 2.0/kg for NO_X, and EUR 0.06/kWh for electricity). The discussion of environmental costs in this chapter illustrates that such costs could be assigned a higher value. However, most of the environmental estimates discussed are averages based on many studies. Generally speaking, they are based on US research. Differences in incomes, tastes, WTP and other factors call into question the appropriateness of using these estimates to analyse projects in different regions or countries. Nevertheless, they give a good indication of environmental costs in a CBA, and of the price range which should be covered by the sensitivity analysis.

The taxes on the NO_X emissions which the Norwegian government has introduced are are set to represent the installation cost of new (existing) technology for reducing these emissions. The current NO_X tax is expected to increase by about 400% in near future to ensure a better match with the cost of installing low-NO_X technology.

2.3 Theoretical foundation

The following theoretical foundation and disciplines are utilised in this study:

- Systems engineering
- Gas flow in pipelines
- Gas pipeline inventory
- Compressor performance
- Gas turbine performance related to emissions
- Statistical analysis
- Operations research (OR) - optimisation
- The system for booking and shipping on the NCS
- Cost-benefit analysis

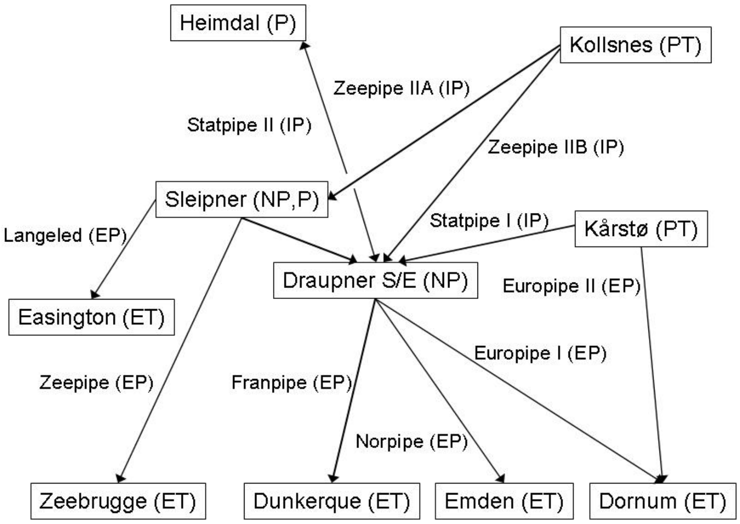
The theory of gas flow in pipelines and the system for booking and shipping on the NCS are presented in appendices H and G respectively. Systems engineering theory is presented in chapter 3, the theory of pipeline inventory is presented in chapter 4, the theory of compressor and gas turbine performance is presented in chapter 5, the applied statistical theory is presented in annex B in Paper I, optimisation theory is presented in chapter 6, and the theory of CBA is presented in chapter 7.

3 Problem solving methodology

3.1 Introduction

The purpose of this chapter is to present a methodology for attacking and solving the main objective of the work[1]. This supports objective A. In paper IV, the systematic methodology established and applied in order to analyse and solve the main objective is described. In the following main results from this work is presented.

The Norwegian dry gas export system (NDGES) is the system-of-interest, and the subject for analysis and model development in this work. Figure 3–1 shows this system, which forms part of the total gas transport network on the NCS (Fig. 1–2). The notations describe the function of each element in the figure.



Notations:

EP	Export pipeline - pipeline where the pipeline outlet is connected to an exit terminal
ET	the point/terminal where the customer nomination will be delivered (and gas leaves the network)
IP	Intermediate pipeline - pipeline, which not terminates at an exit terminal
NP	Node platform - platform that connects more pipelines together
P	Production platform - platform where a production of gas occurs, and gas comes into the network
PT	Processing terminal - terminal where gas is processed and compressed and comes into the network

Figure 3–1: System-of-interest - the Norwegian dry gas export system

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1) In further sections of this chapter the terms main problem and sub-problems are applied for main objective and goals respectively.

The NDGES is a large and complex system, and it can be difficult to obtain a clear and total overview of this system, its relations, interactions, operation and causal connections. Furthermore, optimisation of system operation is a comprehensive task which requires an integration of several technical disciplines and concerns all the physical components of the system. The main objective, however, concerns optimisation of the whole system and not solely of individual components. This will imply several trade-offs since optimum operation of one component generally does not result in optimum operation of another component in the system.

3.2 Systems engineering principles

The tool to overcome the challenges presented above is based on system engineering (SE) principles. The focus in SE is on optimisation of and finding solutions for a whole system, rather than individual system elements, and the use of SE should lead to more rationale decisions and to greater reliability and applicability of the solutions.

According to INCOSE [35], SE is an interdisciplinary approach and involves enabling the realisation of successful systems. Asbjørnsen [2] regards SE as a discipline which involves the analysis, understanding and design of the functional, operational, physical and interface characteristics of large integrated systems with many different elements and subsystems. It also considers the impact on and interactions with the environment. The SE discipline is an effective way to manage complexity and change. Eisner [23] regards SE as a process of top-down synthesis, development and operation of a real-world system which satisfies, in near optimum manner, the full range of requirements for the system.

3.3 Information models

Information models have been developed to analyse the main problem and the system-of-interest. Paper IV presents and examines these models. However, the main models are presented here.

Figure 3–1 shows the dry gas export subsystem on the NCS which is the subject of analysis. Figure 3–2 illustrates an architecture model of this system, and shows how the system is physically built up from system elements and subsystems. Each pipeline in the model is connected to one plant at the pipeline inlet and one plant at the pipeline outlet.

Decomposition of the main problem into sub-problems is necessary owing to the complexity of the main problem and the need for various skills and methods to solve the different sub-problems. Figure 3–3 shows the relationships between the models which will be established, the system and subsystems, the related problem and sub-problems, and the tasks required after model development: evaluation, validation and implementation. It also shows how the models and tasks are related to the work objective and goals, as described in section 1.3, and the corresponding papers which have been written and form the basis for the work.

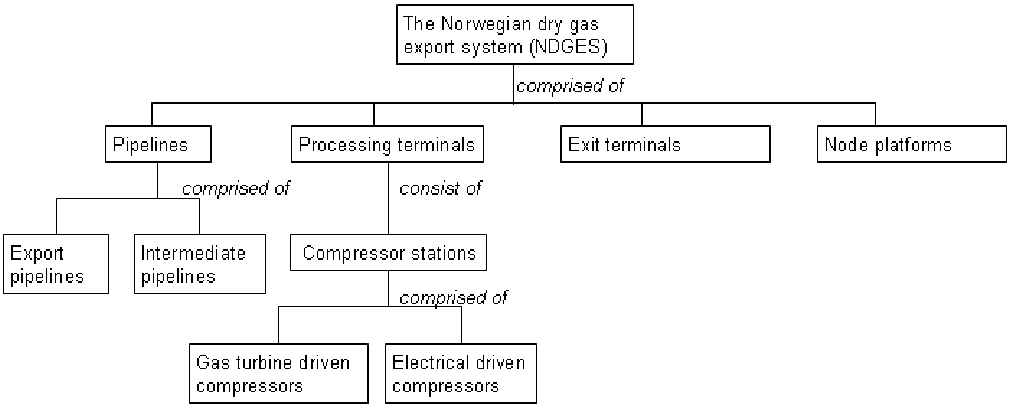

Figure 3–2: Model of the system elements and subsystems of the NDGES

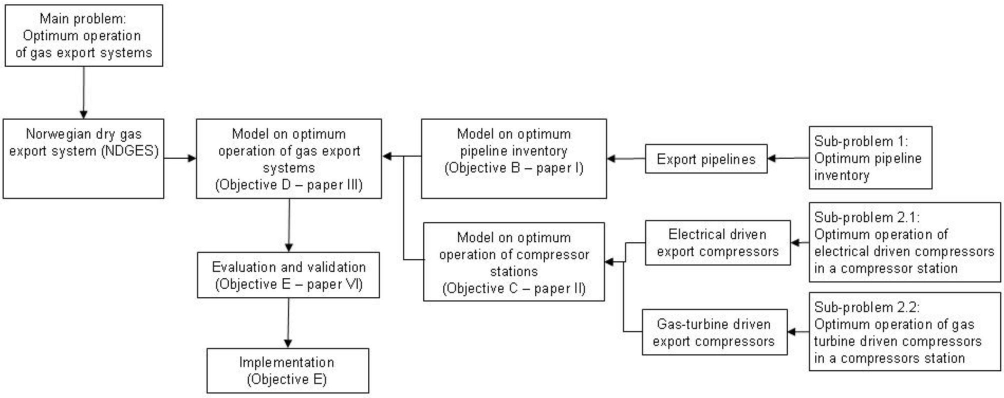

Figure 3–3: Relationships between sub-problems, system elements, subsystems and system-of-interest and solution models.

3.4 System objectives and requirements

The formulation of system objectives follows the problem statement presented in section 1.3:

> *Establish a model and guidelines on gas export system operation which increase system energy efficiency and reduce environmental emissions while fulfilling customer nominations, and which will be implemented in actual system strategic planning and operation.*

Evaluation of the problem statement reveals two categories of objectives, which the gas export system must meet:

- satisfy customer nominations - delivery security
- minimise power consumption and environmental emissions - energy efficiency.

Following the objectives is an identification of requirements - economical, technical and legal - and control variables related to each system element. This is necessary to necessary to ensure a valid and satisfactory solution and to consider all alternative ways to modify system operation. Figure 3–4 displays the relationships between system elements, tasks (requirements) and control variables. Each system element will impose a requirement to another connected system element, and each element only sees the connected elements. Furthermore, each system element contains certain control variables which will be varied in order to meet the requirements and fulfil the tasks.

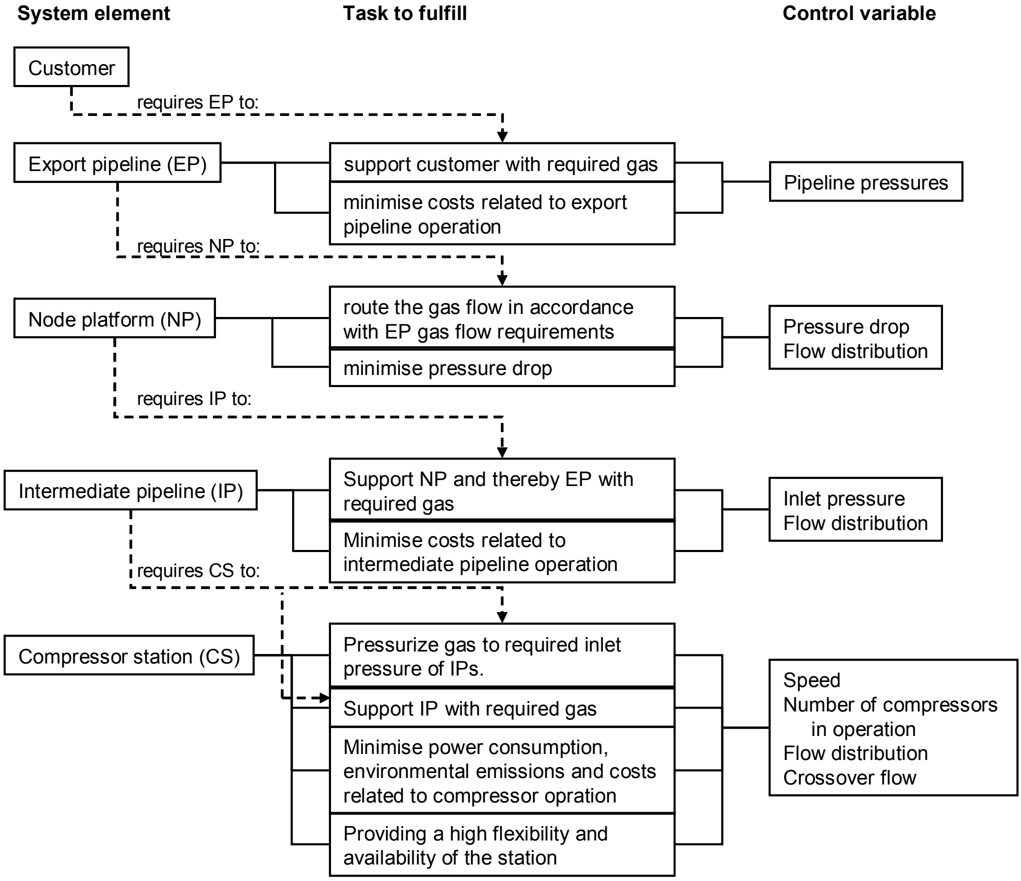

Figure 3–4: Requirements and control variables belonging to each system element

The process starts with the customers at the exit terminals, who require a certain amount of gas to be delivered from the export pipelines. For the export pipelines, this also implies the need to be prepared for sudden potential increases in customer demand. Furthermore, the export pipelines are connected to a node platform or a compressor station at processing terminals (see Fig. 3–1). The node platforms receive requirements from the exit terminals concerning the required gas flow, and transmit requirements to the intermediate pipelines. Compressor stations at processing terminals receive requirements concerning flow and pressures. In addition, each element is required by the operator and owner to operate as economically and as energy and/or environmentally efficiently as possible. The importance of providing high availability[2] and flexibility[3] is especially applicable for compressor stations. Physical requirements concerning capacity limits also exist for each element.

Control variables will be varied to meet the requirements and to optimise system operation. Optimising only one element will not necessarily result in the best operation of the whole system because of contradictory objectives. Optimising the system solely with regard to customer nominations imply maximising export pipeline inventory and thereby pressures in order to achieve full operational flexibility (for gas deliveries). This further requires a high compressor discharge pressure. Compressing the gas to a high pressure increases power consumption and thereby costs and emissions. However, optimising operation with regard to energy efficiency implies reducing compressor power consumption. In most cases, this will result in reduced discharge pressure and pipeline inventory, and thereby weaken the ability to deliver gas to customers who may make varying gas nominations. Furthermore, because of high export gas volumes in general, compressor stations must comprise several compressors in order to provide sufficient capacity. Each compressor has a favourable operating range in terms of energy efficiency. If a certain compressor has a required flow to fulfil and its performance efficiency is to be maximised, the result will be a specific compressor discharge pressure. Similarly, if a certain pressure is required and performance efficiency is to be maximised, the result will be a specific compressor flow rate. However, the pipelines connected to the compressor station require a specific gas flow rate at a specific pressure, in accordance with customer nominations. Therefore, each compressor may not be able to operate in its most efficient operating range. Table 3–1 shows the effects of varying, maximising and minimising, the control variables for each system element.

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2) Following Blanchard and Fabrycky [6], availability is defined as the degree to which a system or subsystem is operable and in a committable state at the start of operation or when called for at an unknown random point in time.

3) Flexibility is defined as the ability to adapt to a new environment and/or conditions.

Table 3–1: Impact of control variable variations

System element	Control variable [a]	Results by varying control variables	
		Maximising	**Minimising**
Export pipeline	Pipeline pressures	Maximising pipeline inventory and thereby operational flexibility	Reducing upstream pressures and thereby costs related to inventory
Node platform	Pressure drop	Maximising operational flexibility	Reducing upstream pressures and costs related to pressure drop
	Flow distribution	Flow variations in connected downstream pipelines	
Intermediate pipeline	Inlet pressure	Increasing pipeline inventory and thereby operational flexibility	Reducing compressor discharge pressures and related costs
	Flow distribution	Flow variations in connected downstream pipelines	
Compressor station	Speed	Increasing discharge pressure, and thereby pressures and inventory of connected pipelines	Reducing discharge pressure, compressor power consumption and emissions from compressor driver
	Number of compressors	Reducing flow through each compressor	Increasing flow through each compressor
	Flow distribution	Flow variations in connected downstream pipelines	
	Crossover flow	Flow variations in compressors at the same station and in connected downstream pipelines	
		Increases pressure loss over the crossover leg, and thereby compressor power consumption	Reducing operational flexibility

a) The control variable flow distribution can be varied. However, total flow through elements must equal total required flow from connected elements.

Each subsystem or system element has a required function to perform. The functions can be represented by inputs and outputs to the subsystems, and mathematical functions which convert inlet to outlet data. A thorough description of the optimisation procedure is provided in chapter 6.

3.5 Solution methods

Each sub-problem presented in Fig. 3–3 will be solved by establishing sub-models. The sub-models will be aggregated into an overall optimisation model of the system-of-interest. In the model on optimum operation of gas export systems, the configuration of the optimal system operation will be determined as a result of minimising the total specific power consumption or operating costs. Several mathematical equations describe system performance, and will be formulated as constraints in the models. Control variables will be varied in order to achieve the optimum solution. The best operation implies allowing for energy efficient operation of each system element, and merging these into an optimum solution for the whole system. Further description of the models and model developments are presented in following chapters.

Different methods will be applied in developing the models. These are:

- Collection and statistical analysis of operational data (Applied to goals A, B, C, D and E)
  Collection and analysis of empirical data, operational procedures, experiences and constraints constitute a mapping of current system operation, detect typical trends, and provide a basis for model development.
- Probability distribution identification (Applied to goal B)
  Probability distribution identification is used on a given set of data which has an unknown distribution to find the distribution which best fits the data set. This will be used to predict the response for a new observation with a given set of predictor values. Identification of the best distribution is based on probability plots and goodness-of-fit statistics, which evaluates the fit of a distribution.
- Regression analysis (Applied to goals B, C and D)
  Regression analysis is applied to find the best estimate of the relationships between variables, when some inherent relationships exist among them. Regression analysis models the relationship - linear quadratic or cubic - between a response and predictor(s), where both response and predictor(s) are continuous variables. The method used to draw the curve is the least-squares criterion.
- Compressor and pipeline simulation (Applied to goals B, C, D and E)
  Simulation of system components is performed in order to analyse and describe (or model) their actual performance
- Parameter tuning (Applied to goal C)
  Dimensionless coefficients are a typical way of specifying the performance of compressors, independent of inlet temperature and pressure, molecular weight and speed. The influences of the latter (parameters) on the performance coefficients can be adjusted in accordance with actual performance by varying the exponents of the parameters in the equations.
- Linear and non-linear mathematical programming (Applied to goals C and D)
  Mathematical programming is used to develop an algorithm - a mathematical representation - describing system performance which can be implemented in software programmes.
- Constrained non-linear optimisation (Applied to goals C and D)
  Optimisation is used to find the best system operation by optimising an objective function subject to certain restrictions concerning system performance, relations, and capacities. Karush-Kuhn-Tucker conditions are applied to solve constrained non- linear optimisation problems.

3.6 Conclusions

This chapter supports goal A by analysing the relationships in the gas export system and its operation, structuring the main problem and establishing principles for attacking the main problem of the study by means of SE. The work is described in greater detail in Paper IV. A detailed description of the sketched models and solutions follows in the next chapters.

This work has helped to overcome the complexity of the main problem and the system-of-interest. Models have been developed which increase knowledge of causal connections in system operation. This implies identifying the variables which govern the operation of system elements, their impact on system performance, and how they can be adjusted to ensure a valid and optimum solution.

4 Optimum pipeline inventory

4.1 Introduction

The purpose of this chapter is to develop recommendations for an optimum level of export pipeline inventory which provides sufficient operational flexibility and reduces inventory operating costs. This chapter contains the background information for Paper I and supports objective B. The main results and conclusions from the paper are presented. Furthermore, the consequences of operating in accordance with the recommendations are analysed. This analysis is presented more thoroughly in Paper VI.

Gas customers at exit terminals have the opportunity to make varying gas delivery nominations. Meeting these sales gas commitments is important. Upstream from the export pipelines, gas treatment plants process and pressurise the export gas and deliver it into the pipelines. In the event of shutdowns at these plants, the gas supply to the pipeline may be reduced or stopped. To compensate for increased nominations and decreased gas supply to export pipelines, some sort of buffer is necessary. Pipeline inventory, which refers to the total amount of gas in a pipeline, will work well as such a buffer. However, because of the customer’s opportunities to vary nominations from day to day and within a day, and the unexpected occurrence of shutdowns, it is hard to forecast exactly the amount of gas should be delivered at the exit terminals, and consequently to plan the amount of inventory which must be available in the pipeline.

The most energy- and cost-effective way of transporting gas is to operate at the lowest possible pressure and inventory. However, this reduces operational flexibility and poses a risk of gas sale losses. On the other hand, operating the pipelines with a high inventory increases compressor utilisation and thereby environmental emissions. Finding the optimum inventory level becomes a trade-off between reducing inventory-related energy consumption and operational flexibility.

4.2 Theoretical foundation and research procedure

4.2.1 Theory of pipeline gas flow and inventory

Some basic pipeline relationships between steady state flow rates, pipeline pressures and pipeline inventories provide a foundation in models on pipeline operation.

In order to calculate pipeline inventory, I, at standard conditions, the pipeline gas volume (inventory) at standard conditions must be related to the pipeline volume at actual conditions:

$$\left(\frac{p \cdot V}{Z \cdot R \cdot T}\right)_{pipe} = \left(\frac{p \cdot I}{Z \cdot R \cdot T}\right)_{std} \tag{1}$$

The gas constant, R, will be the same in both actual pipeline and standard conditions, the compressibility factor, Z_{std}, equals 1 in standard conditions. Pipeline inventory, I, can therefore be described as:

$$I = \frac{p_{pipe}}{p_{std}} \cdot \frac{T_{std}}{T_{pipe}} \cdot \frac{V_{pipe}}{Z_{pipe}} \tag{2}$$

Pipeline pressure, p_{pipe}, temperature, T_{pipe}, and compressibility factor, Z_{pipe}, vary with pipeline length, and pipeline inventory is calculated by integrating over the whole length.

The relationship between pipeline steady state flow rate, inlet pressure and discharge pressure is given by the following equation:

$$Q_{std} = k \cdot \sqrt{p_i^2 - p_d^2} \tag{3}$$

In the equation, k is a constant which represents pipeline length and diameter, gas gravity, temperature along the pipeline, compressibility factor and friction factor. Derivation of the equation is given in Appendix G. (By combing Eqs. (2) and (3), pipeline inventory can be related to the pipeline steady state flow rate.)

In this work, Pipeline Studio[1] simulation software is applied for analysing and validating flow, pressure and inventory relationships in system pipelines. The performed simulations, are based on the following:

- BWRS equation of state
- Constant sea temperature equal to october average temperature[2]
- Colebrook-White friction factor (in the gas flow equation, Eq. (3))
- Lee, Gonzales and Eakin's empirical correlation of the viscosity

4.2.2 Flow rate/inventory envelope

A flow rate/inventory envelope describes the relationship between pipeline steady state flow rate and available inventory. Figure 4–1 shows the envelope for a pipeline. The upper curve in the figure shows the maximum inventory for the pipeline. The curve is constructed by keeping the pipeline inlet pressure constant at the maximum value while varying the discharge pressure. Decreasing discharge pressure will increase pipeline steady state flow rate in accordance with Eq. (3), and decrease pipeline inventory in accordance with Eq. (2). When pipeline discharge pressure reaches the minimum pressure limit, pipeline flow rate equals pipeline capacity. The opposite applies for the minimum inventory curve: the discharge pressure is held constant at the minimum value

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1) Pipeline Studio is a trademark of Energy Solutions International

2) This is considered the month with the warmest sea temperature, and thus the one when the gas reaches its lowest density. Owing to this assumption, some empirical operational points will lie outside the calculated pipeline inventory limits.

and the inlet pressure is varied. The space between the maximum and minimum inventory curve shows the operating range of a pipeline. At full utilisation, no operational flexibility exists.

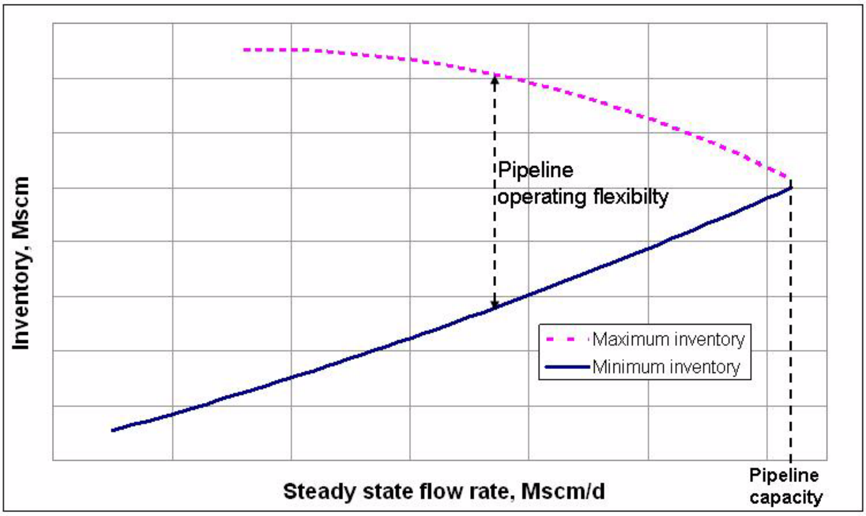

Figure 4–1: Flow rate/inventory envelope for a pipeline

For each pipeline in the system, simulation and regression are applied to develop two regression curves and related equations describing the relationship between steady state flow rate and pipeline inventory (Eqs. (4) and (5)).

$$I_{max} = f(Q) = a_1 + a_2 Q + a_3 Q^2 \tag{4}$$

$$I_{min} = f(Q) = b_1 + b_2 Q + b_3 Q^2 \tag{5}$$

4.2.3 Development of recommended inventory curves

Paper I presents an analysis of historical operational data for flow rate and changes in flow rate values for a pipeline. Probability distribution identification is used to find the distribution which best fits the data. This distribution is applied to estimate expected increases in flow rates out of the pipeline. The expected increases are combined with the pipeline flow rate/inventory curves by relating the increases to minimum inventory. This results in recommended inventory values for each pipeline flow rate value. Regression analysis is employed to find the recommended pipeline inventory curve and equation. Simulations combined with regression analysis are employed to find the corresponding recommended pipeline pressure curves and equations. Recommended curves are compared with actual operation by plotting historical operational data together with these curves. Normalising the curves for all export pipelines will detect similarities and may simplify implementation of the curves in actual operation.

Transient simulations of system pipelines operating in accordance with the recommended inventory and pressure curves are performed in order to analyse the consequences for nomination fulfilment (presented in Paper VI). Given that decreased delivery (shortfall[3]) is to be avoided, the following two aspects are evaluated:

- possible size of a nomination increase within a nomination lead time[4] of two hours
- possible length of complete shut-down directly upstream from an export pipeline.

Furthermore, the results of this consequence analysis are compared with historical gas export system events relating to nomination increases and shutdowns over the past three years.

4.3 Results from pipeline inventory analysis

The following results are presented in greater detail in Paper I (with regard to optimum pipeline inventory) and Paper VI (with regard to consequences for delivery security). Validation of the model results and pipeline simulation software against the actual physical performance of system pipelines is also presented in Paper VI.

4.3.1 Recommended inventory curves

Figures 4–2 and 4–3 show the resulting recommended inventory and corresponding inlet and discharge pressure curves respectively for one specific pipeline. In Fig. 4–2, historical data from the past three years are included for comparison.

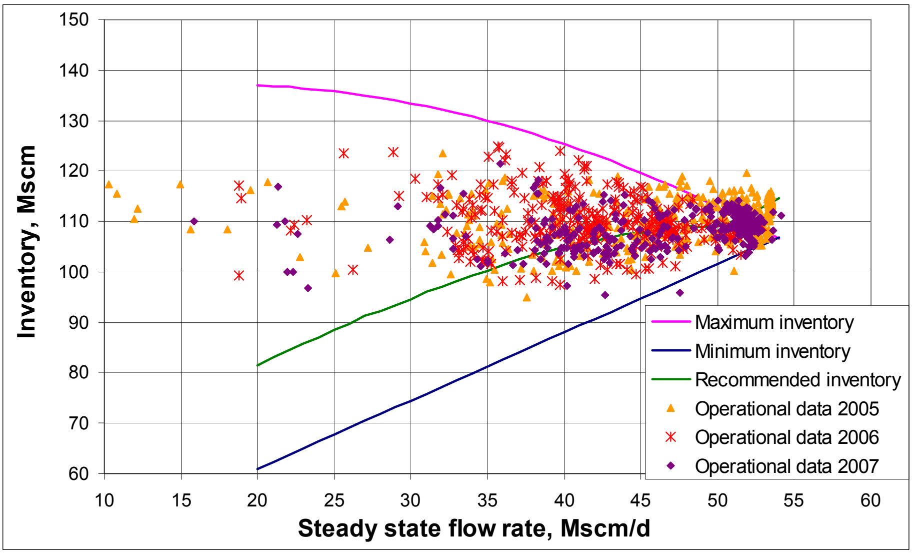

Figure 4–2: Recommended pipeline inventory curves and actual historical operational data

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3) Shortfall refers to the amount of gas not delivered to customers in accordance with their bookings within a day.

4) Lead time is the time required by the operator to process nominations and schedule the changed flow.

Figure 4–2 shows that at average pipeline utilisation of approximately 70-80%, pipeline inventory in actual operation from the past three years is about 5% higher than the recommended level. For low pipeline capacity utilisation of 60% the difference may be up to about 30%. At higher utilisation the trend is that actual operating inventory level equals the recommended level.

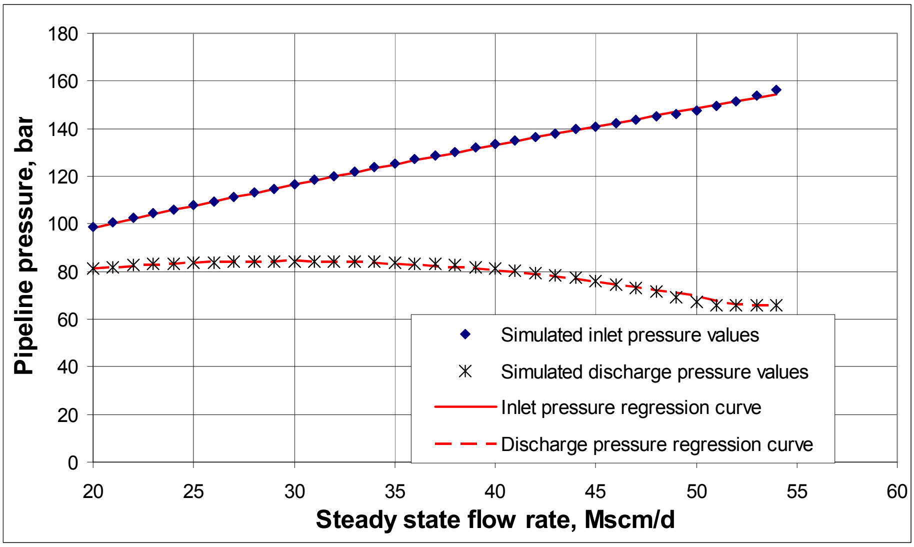

Figure 4–3: Recommended pipeline pressure curves

Equations describing recommended inventory and pipeline curves are as follows:

$$I_{rec} = c_1 + c_2 q + c_3 q^2 + c_4 q^3 \tag{6}$$

$$p_{i,\,rec} = d_1 + d_2 Q + d_3 Q^2 + d_4 Q^3 \tag{7}$$

$$p_{d,\,rec} = e_1 + e_2 Q + e_3 Q^2 + e_4 Q^3 \tag{8}$$

Figure 4–4 shows maximum, minimum and recommended inventories for three pipelines on a normalised basis: Europipe II, Franpipe and Zeepipe.

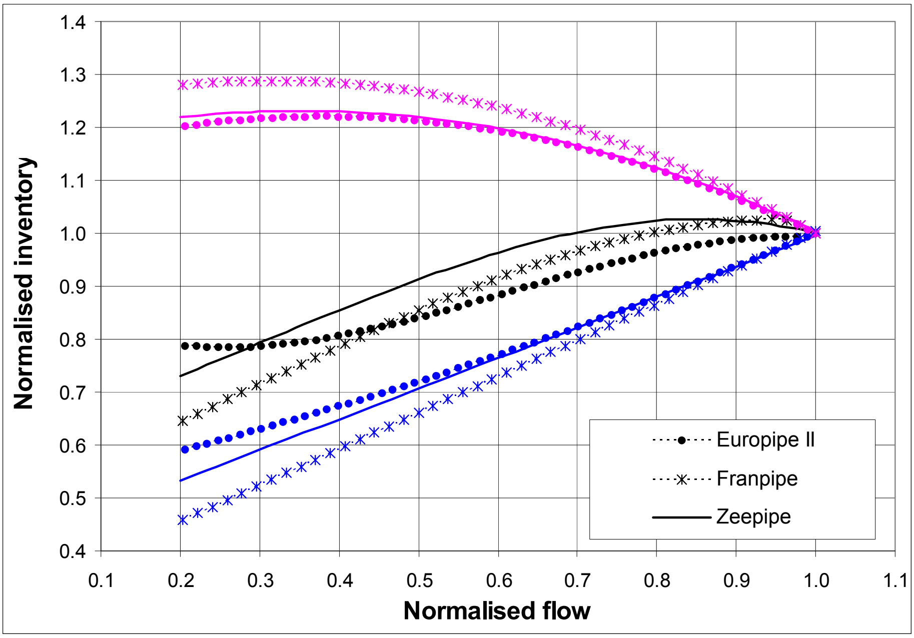

Figure 4–4: Normalised flow rate/inventory envelope for export pipelines

The analysis confirms that these values are relatively equal for all export pipelines. A common visual display for all export pipelines can therefore be applied in actual operation. (See chapter 8, implementation.)

4.3.2 Consequences for delivery security

Nomination increase

With a nomination increase, discharge pressure may be reduced down to the minimum pressure limit. The flow rate into the pipeline could increase initially up to maximum pipeline capacity in order to achieve sufficient gas inventory for nomination fulfilment. Figure 4–5 illustrates how large a nomination increase relative to the initial flow rate is possible at different flow rates relative to maximum pipeline capacity.

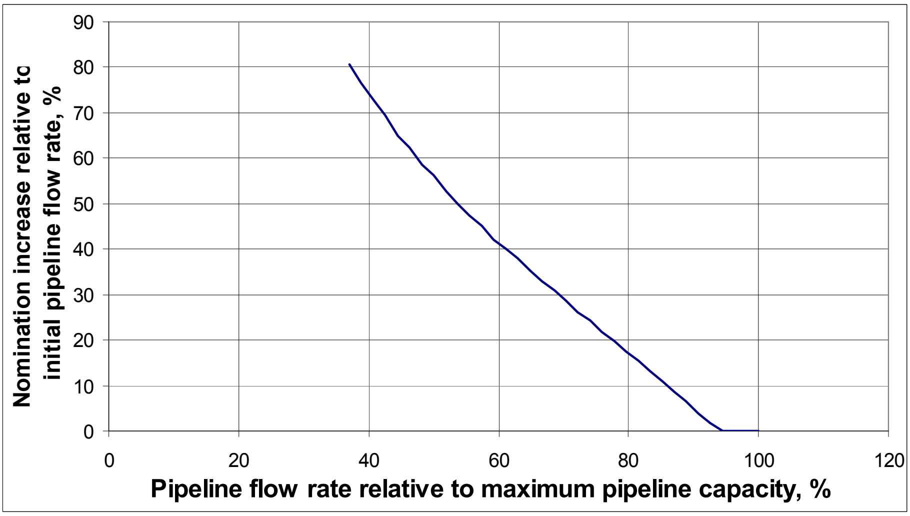

Figure 4–5: Possible relative increase in nomination as a function of relative initial flow rate by recommended operation

The figure shows that flow rates in the range of 0-85% of maximum flow rate can cope with nomination increases of more than 10% of initial pipeline flow rate. At a flow rate of 94%, the recommended discharge pressure equals the minimum pressure limit, and no more opportunities exist to increase flow out of the pipeline.

Analyses of historical data have discovered that nomination increases higher than 10% are rare events, i.e, less than 25 days per year (6.8%). At flow rates higher than 94% (58 days per year on average), nomination increases have only happened 13 times per year on average (3.6%), and the maximum increase was 3.7%.

Shutdowns

Figure 4–6 shows how long a constant flow rate out of the pipeline can be sustained by using the recommended inventory during a complete shutdown represented by zero gas flow into the pipeline.

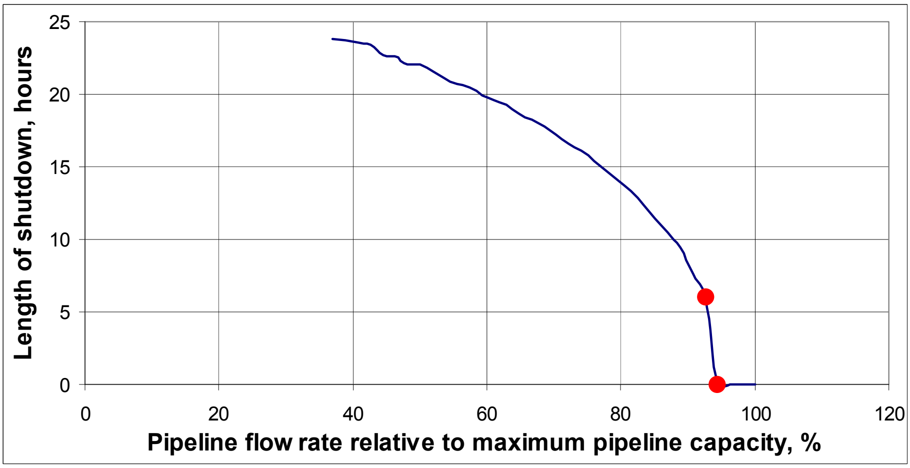

Figure 4–6: Possible length of a complete shutdown for different relative pipeline flow rates without a shortfall through recommended operation

Figure 4–6 shows that, for initial flow rates below 92.6% of maximum pipeline capacity, it takes more than six hours before the discharge pipeline flow rate must be reduced after a complete shutdown. Flow rate values higher than 94.4% of maximum pipeline capacity have no flexibility when it comes to shutdowns, because discharge pressure has already reached the minimum. (Red circles.)

Shutdown analyses have identified that:

- 80% of the shutdowns at any size lasted less than six hours
- shutdowns which last more than six hours have happened four times a year (1.1%) on average
- 80% of the shutdowns were lower than 27.8% of maximum pipeline capacity
- shutdowns in the range of 50-100% of full capacity have only happened twice a year on average
- the commonest duration of a shut-down was approximately 2.5 hours
- the commonest reduction in flow rate into the pipeline was 7.5% of maximum pipeline capacity

These above presented aspects show that extremely large (above 50% of capacity) or long shutdowns (above six hours) which have considerable impact on the ability to deliver are very rare.

Two simulations were executed on the basis of the values for the typical duration of a shutdown and the typical reduction in the size of flow into the pipeline. Figure 11 in Paper VI shows that flow rates lower than 80% of maximum pipeline capacity can experience a complete shutdown for the simulated typical duration and still maintain a constant flow out of the pipeline. Figure 12 in Paper VI shows that at flow rates below 83% of maximum capacity, the duration of a typical shutdown in terms of size must exceed two days before the discharge pipeline flow rate will be reduced.

4.4 Discussion

The work has shown that, for most export pipelines, the inventory can be reduced compared with the former level as long as the pipeline is not operating at full capacity (Fig. 4–2). The limit is approximately 80% of maximum pipeline capacity. In actual operation, the trend is that inventory values have been relatively stable regardless of the actual pipeline flow rate. Cutting inventory implies lowering pressure and thereby reducing upstream compression and related operating costs.

Furthermore, analyses of historical data concerning nomination increases and shutdowns confirm that operating in accordance with the established recommended inventory curves provides sufficiently high levels of pipeline inventory in most cases. Customer nomination will be fulfilled and shortfalls avoided. However, for flow rates above about 94% of pipeline capacity, no flexibility exists in the recommended levels. The recommended curves should therefore be employed mainly when flow rates are below this value.

The lead time from a renomination until the discharge pipeline flow rate increases is assumed in the analysis to be two hours. This represents an extreme case. Capacity in the pipelines is booked on an annual and monthly basis, and shippers' nominations are made weekly and within a day. The operator therefore knows roughly the amount of gas that is to be delivered from day to day, and therefore also the nomination changes which will occur. This allows sufficient (recommended) inventory to be prepared in advance.

When a shutdown has occurred, shippers with gas nominations at the affected delivery points are notified of the event. A common reaction by the shippers is to reduce their nominations, although this is not necessarily required. This reaction may reflect the desire of the shippers for certainty. By reducing their nominations in accordance with pipeline inlet capacity, they know for certain how much they are able to deliver. When the affected equipment restarts, the shippers are able to resume with full delivery immediately.

According to the presented results, however, export pipeline inventory is high enough in most cases to compensate for the shutdowns, and complete delivery in accordance with the nominations can be maintained at the exit points. Certainty is often chosen at the expense of seeking to fulfil customer nominations, and this results in gas sale losses for the shippers. The established curves may provide security and a confirmation to gas shippers that downward adjustments (lowering customer nominations) are not needed.

An aspect which has not been considered in the development of a recommended pipeline inventory is the possibility of shutdowns downstream from the export pipelines. In such cases, it is important to maintain production of both oil and gas on upstream installations, and thereby to continue delivering gas into the pipeline. Oil and gas production are usually tightly related. Halting gas production also affects oil production, causing large financial losses as a result of lost oil sales. To be able to maintain production, a certain amount of spare capacity in the pipeline is required to store the delivered gas. However, the established recommendations (Fig. 4–2) include a certain amount of space available for gas packing.

European spot markets for gas sales are developing. Assuming that all gas not sold under long-term contracts will be disposed in the spot market at a price higher than the sum of gas taxes, production and transport costs, the most profitable approach will be to operate the pipelines at all times at maximum flow rates and capacities since this maximises gas sale revenues. This implies no flexibility with regard to pipeline inventory. According to the system operator, however, gas sold under long-term contracts remains the most important component in deliveries, and export pipeline capacities are not generally fully utilised.

Prospects for gas shipping show that a difference will persist between export pipeline capacity and utilisation in coming years. Pipeline capacities have also expanded continuously in recent years, which may even increase this difference. Reducing pipeline inventory will therefore continue to be relevant and important in the future.

The next two chapters deal with the way to provide export pipelines with the recommended inventory in the most energy and environmentally efficient manner.

4.5 Conclusion

This chapter supports objective B by establishing a method to predict optimum pipeline inventory. Recommended curves are established through statistical analysis of historical operational data. The method is described in Paper I. The study concludes that a potential exists for reducing the inventory in the pipelines. Inventory reduction implies cuts in pipeline pressures and thereby in upstream compression. This results in lower pipeline operating costs.

Paper VI analyses the consequences on the ability to deliver the nominated quantity by operating in accordance with the established recommended curves in the event of nomination increases and/or shutdowns. The analysis concludes that, in most cases, the recommended curves provide a sufficiently high level of inventory and that customer nomination will be fulfilled.

5 Optimum operation of the export compressors

5.1 Introduction

The purpose of this chapter is to analyse the performance of compressors and develop procedures and models on optimum operation of gas export compressor stations. The chapter contains the background and theoretical foundation for Paper II and supports objective C. It presents the main results and conclusions from Paper II and partly Paper III. These results are related to an operational model developed for the Kollsnes export compressor station. This chapter further presents a new mathematical model for operation of the Kårstø export compressor station.

Compressor stations play an important role in gas export systems because they compress the export gas up to the required pressure and deliver it into the pipelines. Given the large variations in operating conditions experienced by gas export compressors, these facilities should be capable of operating over a wide range at high efficiency. An important operational aspect is how to adjust the compressor stations to the varying conditions, and, in particular, how this influences compressor station efficiency.

To achieve the required capacity and flexibility in one compressor station, several compressors arranged in parallel and/or in series as well as crossover legs may be needed. Compressor load sharing, opportunities to start up a new compressor, shut down one in operation or re-route a compressor are methods used to regulate the capacity and maximise the efficiency of compressor stations.

The system-of-interest comprises several compressor stations and possibilities for load sharing between the compressor stations. In addition to several compressors operating in parallel and series, crossover possibilities, compressor degradation, alternating pipeline pressures and nominations, this presents challenges for identifying optimum operating procedures at a compressor station and between stations. However, it also enhances operational flexibility. Several different ways of operating the system compressor stations are available. Each of these may be equal in terms of meeting system requirements, but may differ in terms of energy efficiency. Optimum operation of compressor stations implies increasing the energy efficiency of the compressor stations by minimising specific power consumption, which cuts operating costs and environmental emissions.

The existing export compressor facilities at the Kollsnes and Kårstø gas treatment plants are utilised to develop models of optimum compressor station operation. An overview of these two stations is presented in Figs. 5–1 and 5–2 respectively. The compressors at the Kollsnes export facility are all electrically-driven, while those at Kårstø are driven both by electric motors (EM) and gas turbines (GT), as indicated in Fig. 5–2.

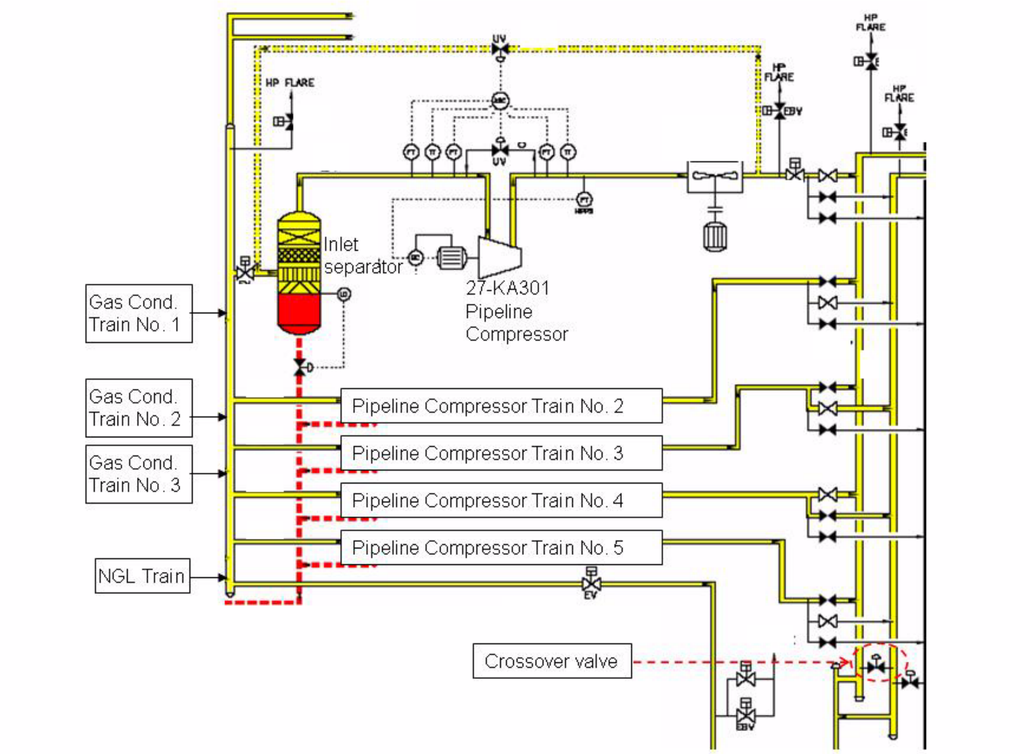

Figure 5–1: Overview of the compressor station at Kollsnes gas treatment plant

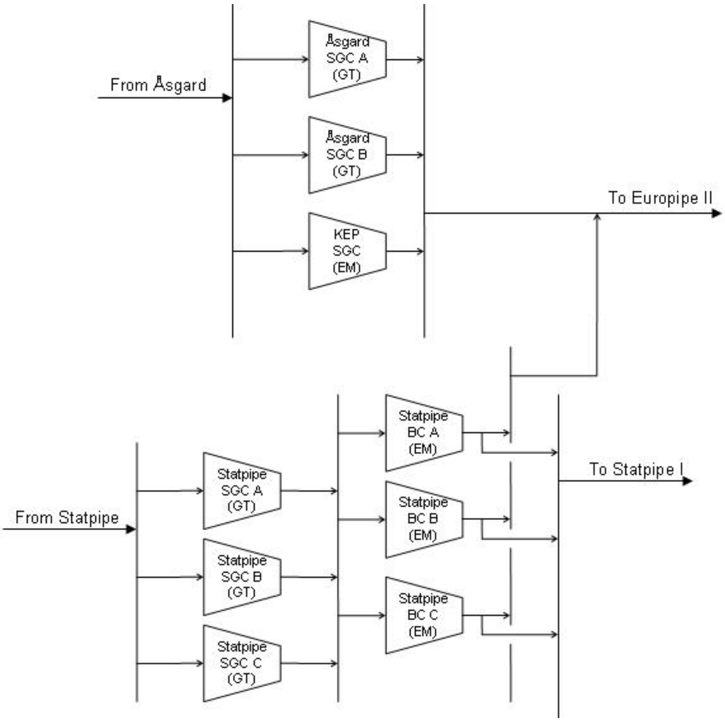

Figure 5–2: Overview of the compressor station at Kårstø gas treatment plant

5.2 Theoretical foundation and research procedure

5.2.1 Compressor operation

Performance characteristics are a common way to represent compressor performance. Figures 5–3 and 5–4 present design polytropic head and polytropic efficiency curves respectively at different speeds for a centrifugal compressor at the Kollsnes export station. The operating envelope of the compressor is limited by the maximum allowable speed, the minimum allowable speed, the minimum flow (surge flow), and the maximum flow (choke or stonewall).

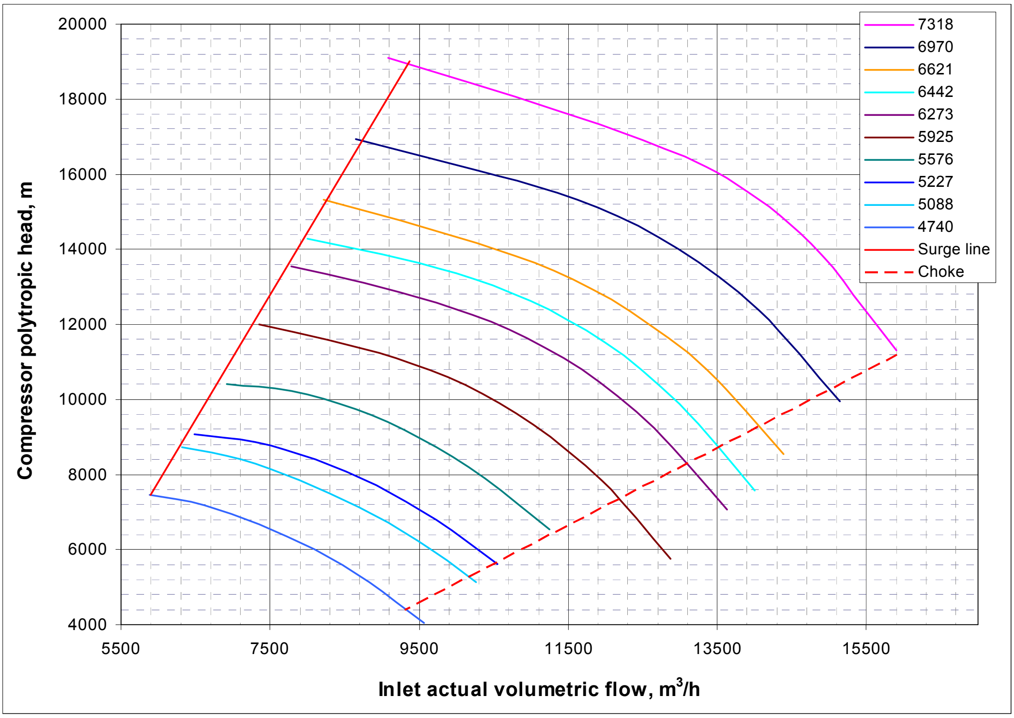

Figure 5–3: Performance characteristics of compressor polytropic head

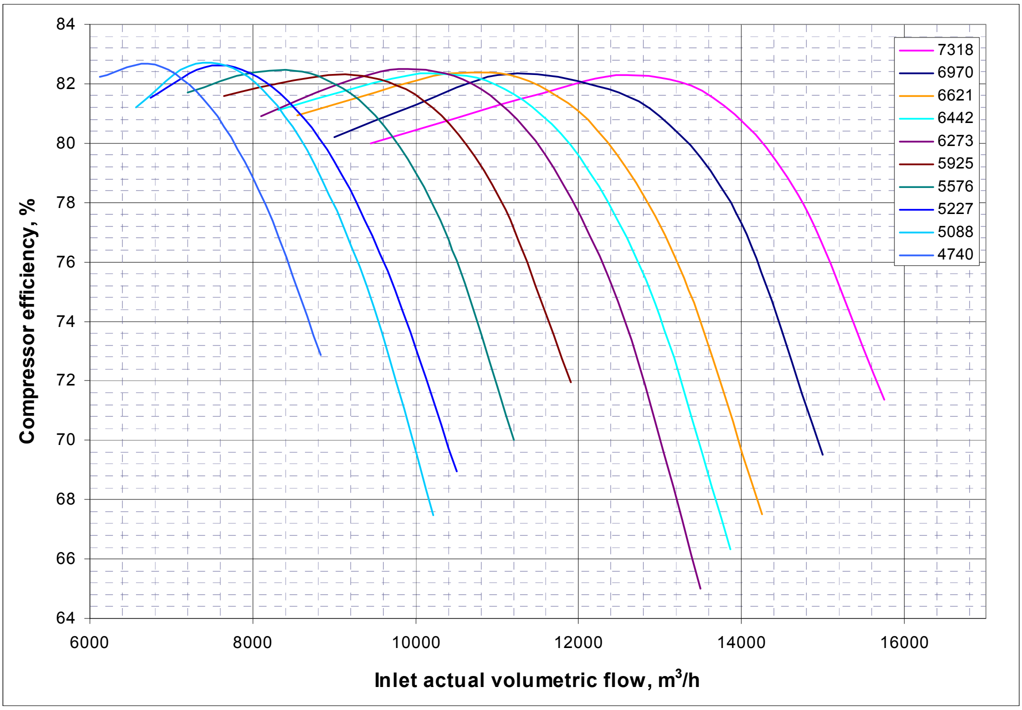

Figure 5–4: Performance characteristics of compressor polytropic efficiency

The performance of a compressor may be specified by equations of different dimensionless parameters. These equations will not be dependent on inlet pressure and temperature, or the molecular weight or speed of the working fluid. The following parameters are used as a basis for evaluating and modelling compressor performance of the compressors in the system.

Flow coefficient:

$$\varphi_c = \frac{\dot{m}_c \times \sqrt{T_{i,c}}}{p_{i,c} \times \sqrt{MW_c} \times S} \tag{9}$$

Pressure coefficient:

$$\omega_c = \frac{p_{d,c}}{p_{i,c} \times S^2} \tag{10}$$

Power coefficient:

$$\psi_c = \frac{P_c \times \sqrt{MW_c}}{p_{i,c} \times \sqrt{T_{i,c}} \times S^3} \tag{11}$$

Performance curves for all system compressors are implemented in the simulation tool, Pro/II[1]. Simulations are performed for varying conditions and compressor speeds, and the performance coefficients described in Eqs. (9)-(11) are modified so that they fit the actual compressors. This is done by tuning the exponents for inlet temperature, inlet pressure, molecular weight and speed. Regression analysis is then performed to find representative mathematical relationships between the coefficients.

The effect of compressor degradation is analysed in Paper II. In the following work a degraded compressor is represented by reducing the compressor polytropic efficiency for all speeds and flow rates by 5%. Performance coefficients for a degraded compressor are established, and the effect of the degraded compressor on compressor station operation is analysed by substituting the degraded compressor for one of the other compressors at the station.

The compressors in the system will be driven by electric motors or gas turbines. A majority of offshore oil and gas platforms have gas turbine-driven compressors. Export compressors at land-based terminals (such as Kårstø and Kollsnes) are driven either by electric motors or by gas turbines. Performance of these drivers will also restrict operation and flexibility of the compressors.

5.2.2 Electric motor performance

Each electrically-driven compressor in the export system is driven through gear boxes by a variable-speed electric motor. Figure 5–5 shows the performance curve for power limitation for the electric motors at Kollsnes gas export station. The curve shows available power for the compressors at different motor speeds. Figure 5–6 shows how power limitation for the electric motors restricts operation of the compressors at Kollsnes for some specified conditions[2].

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1) Pro/II is a trademark of Simsci

2) An inlet temperature of 4 ° C, inlet pressure of 71 bar and a molecular weight of the gas of 17.45 kg/kmol.

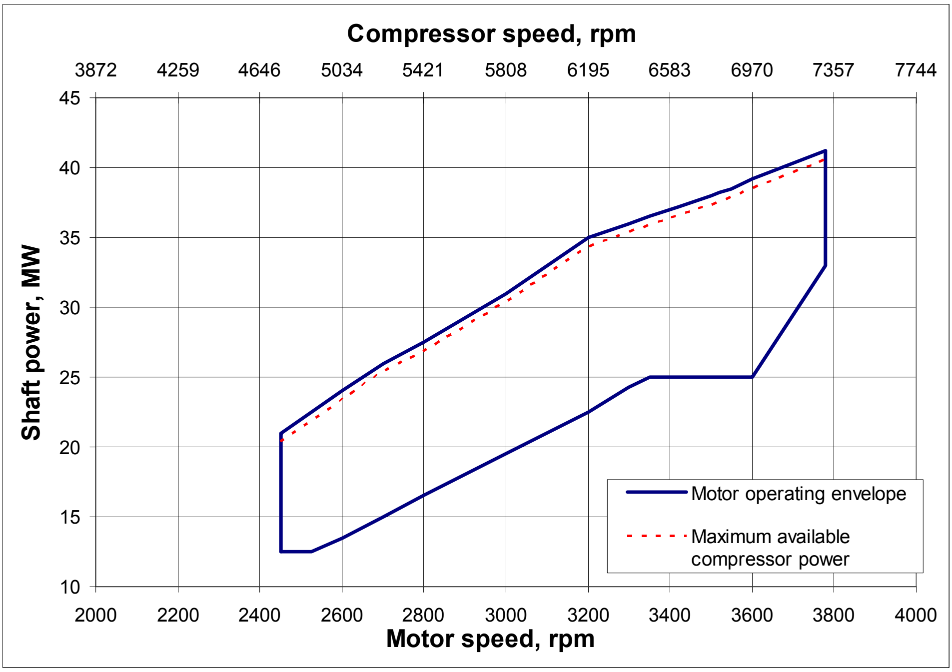

Figure 5–5: Electric motor operating envelope - power limitation

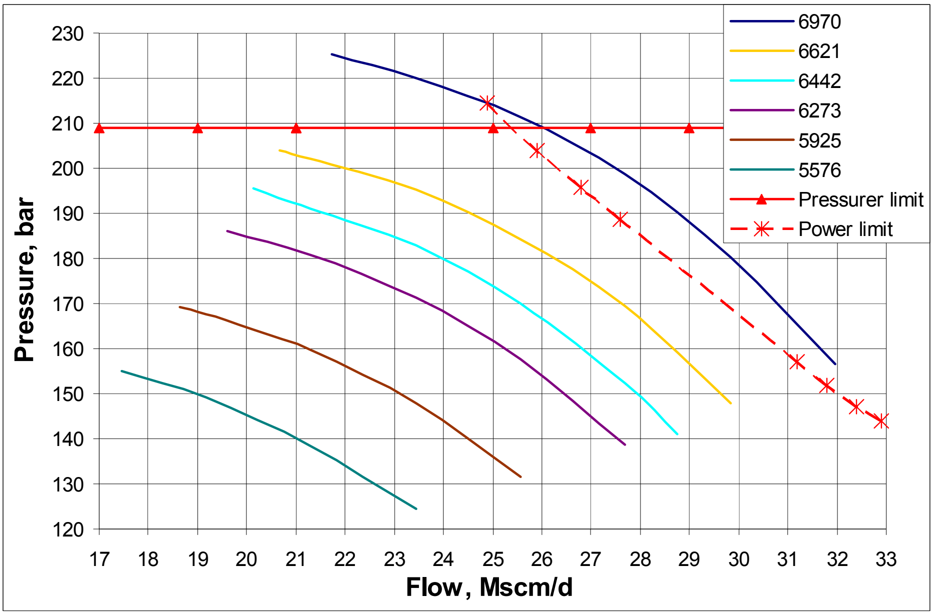

Figure 5–6: Power limitation of the compressor at Kollsnes

5.2.3 Gas turbines

Gas turbine-driven system compressors are also operated through gear boxes and limited by available power. Gas turbine efficiency is directly related to fuel consumption. For the system-of-interest, sales gas is utilised as fuel for the turbines. Figures 5–7 and 5–8 show specific and actual fuel consumption versus turbine shaft power at a specified power turbine speed for a gas turbine at the Kårstø gas treatment plant.

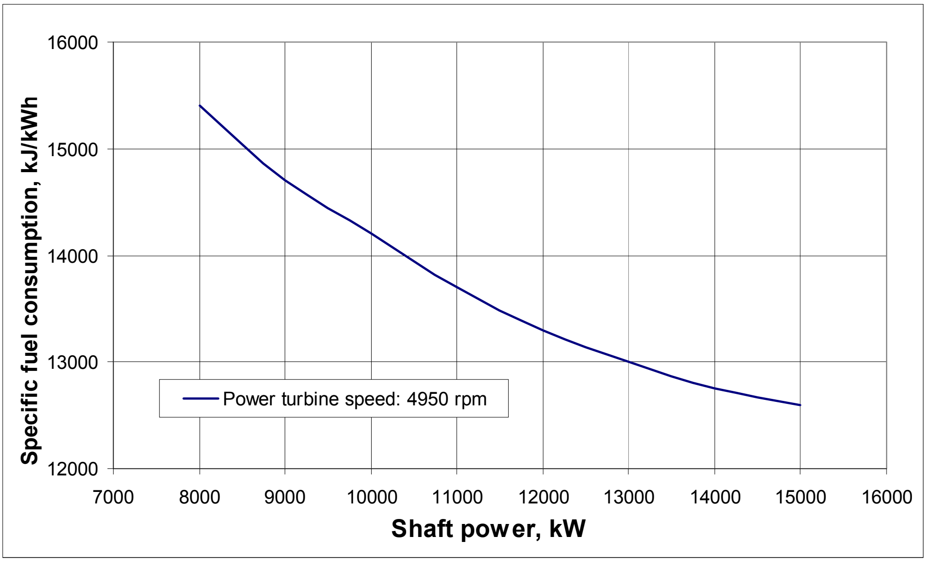

Figure 5–7: Gas turbine specific fuel consumption versus shaft power

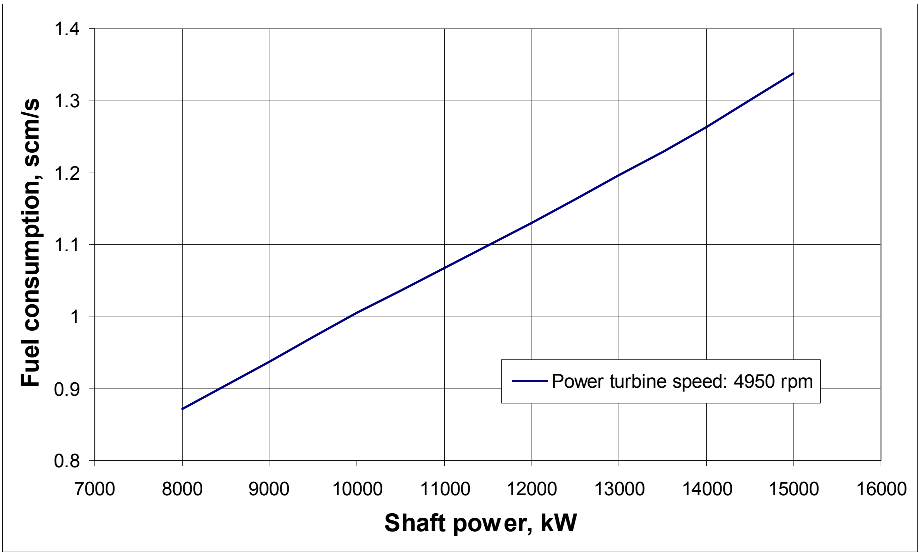

Figure 5–8: Gas turbine actual fuel consumption versus shaft power

Combustion of fuel during gas turbine operation emits such pollutants as CO_2 and NO_X. CO_2 emissions are proportional to fuel consumption, whereas NO_X emissions are proportional to flame temperature, which is related to power and fuel consumption of gas turbines. Taxes on these emissions have been introduced by the Norwegian government and they are proportional to fuel consumption.

5.2.4 Compressor station modelling

Operation of the compressor stations will be described by developing a non-linear mathematical algorithm including dimensionless performance equations, emission from gas turbines, relationships between system compressors and connected pipelines, and other system capacity constraints. By running the algorithm for different operational compressor station configurations, the effect of varying important variables will be found.

5.3 Results from analysis of compressor station operation

5.3.1 Modified dimensionless performance coefficients

Paper III presents the resulting equations for dimensionless compressor performance after tuning the exponents. Figures 5–9 and 5–10 show the relationship between flow and pressure coefficients, and between flow and power coefficients. Compressor simulations have provided the data point for different speeds. The fitted lines are established by means of regression analysis. Operational data show the values obtained by applying the established performance equations to these data.

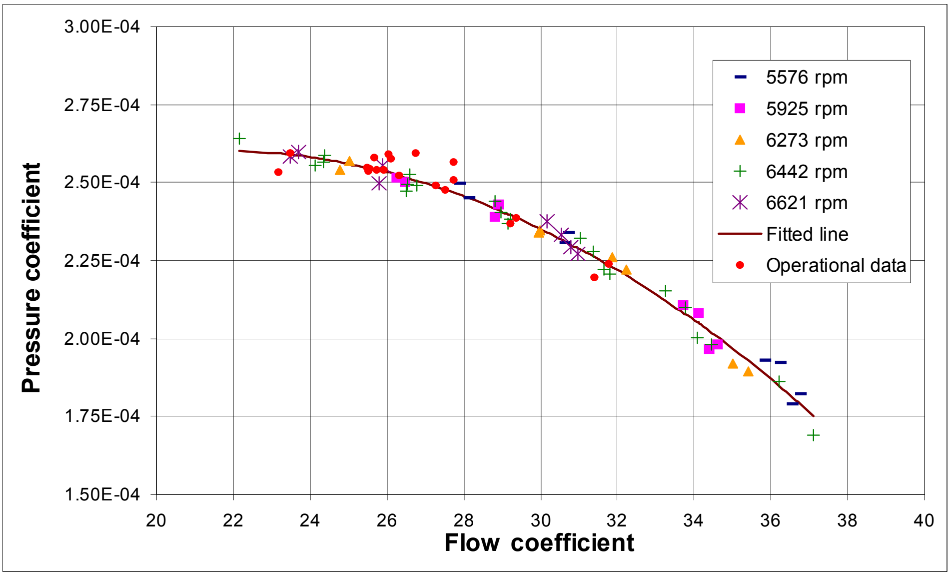

Figure 5–9: Relationship between flow and pressure coefficient for simulated and actual operational data

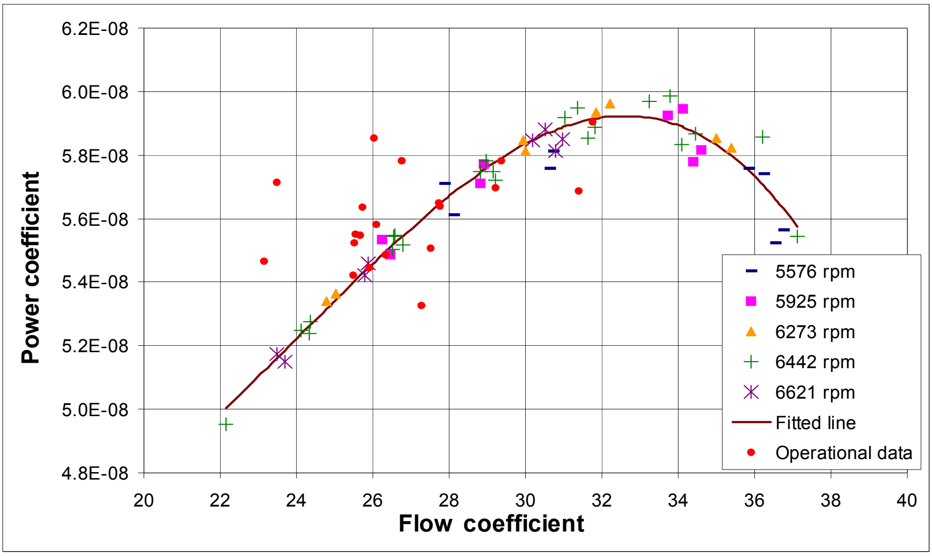

Figure 5–10: Relationship between flow and power coefficient for simulated and actual operational data

5.3.2 Algorithm for operation of export compressor stations

Mathematical algorithms for operation of the Kollsnes and Kårstø gas export compressor stations have been developed. The algorithm related to the Kollsnes export station is given in Paper III. This algorithm is somewhat extended for Kårstø, since its export station comprises both electrically- and gas turbine-driven compressors, and the station configuration is more complex. This section presents the complete algorithm for operation of the Kårstø compressor station, in accordance with Fig. 5–2. The KEP and Åsgard sales gas compressors are two stage compressors with intercooling. This implies that dimensionless flow, pressure and power coefficients are established separately for stages one and two. Throughput and speed are the same for both stages.

Input data

The following parameters provide input to the operational model for the Kårstø gas export compressor station:

- Nomination in Europipe II, $Q_{EuropipeII}$
- Flow in Statpipe I (Kårstø - Draupner), $Q_{StatpipeI}$
- Inlet pressure of Europipe II, $p_{i,\,EuropipeII}$
- Inlet pressure of Statpipe I (Kårstø - Draupner), $p_{i,\,StatpipeI}$
- Compressor suction temperatures, $T_{i,\,c}$
- Compressor suction pressures, $p_{i,\,c}$
- Gas molecular weights, MW_c
- Pipeline and compressor station capacities

Inlet pressure of Europipe II results from calculations of optimum pipeline inventory as presented in section 4.3.1. Inlet pressure of Statpipe I results from the pipeline flow equation, Eq. (3) (Chapter 4).

Control variables

The control variables which will be varied in the operation of the model are:

- Compressor speeds, S_c
- Compressor flow rates, Q_c
- Number of compressors in operation, N_c

Variation of compressor flow rates implies flow distribution between the compressors, and also deciding which of the Statpipe booster compressors (BC) should be directed towards Europipe II and Statpipe I respectively (See Fig. 5–2).

Mathematical system description

The following operational equations apply for the compressors at the station, and act as constraints on the further optimisation. The actual performance coefficients, φ, ω and ψ, are the same for all equal compressors (compressors belonging to the same group, distinguished by the letters A-C in Fig. 5–2), but differ for the different type of compressors. The symbol c represents a certain compressor group, and

$$c = \{SGC, BCI, BCII, KEP1, KEP2, \dot{A}SG1, \dot{A}SG2\}.$$

The Statpipe sales gas compressors (SGC) consist of three compressors,

$$N_{SGC,\,max} = 3.$$

The Statpipe booster compressors (BC) comprise BCI, directed towards Statpipe I, and BCII, directed towards Europipe II, and together they equal three compressors,

$$(N_{BC\bar{I}} + N_{BC\overline{II}})_{max} = 3.$$

KEP1 and KEP2 equal the first and second stages respectively of the KEP sales gas compressor,

$$N_{KEP1,\,max} = N_{KEP2,\,max} = 1.$$

ÅSG1 and ÅSG2 equal the first and second stages respectively of the Åsgard sales gas compressors, which comprise two compressors,

$$N_{\dot{A}SG1,\,max} = N_{\dot{A}SG2,\,max} = 2.$$

Actual compressor flow coefficient:

$$\varphi_c = \frac{Q_c \times \sqrt{MW_c} \times 1.76321 \times T_{i,c}^{ex1}}{p_{i,c} \times S_c} \tag{12}$$

Actual compressor pressure coefficient:

$$\omega_c = \frac{p_{d,c}}{p_{i,c}} \times \frac{T_{i,c}}{(S_c / 10000)^{ex2}} \tag{13}$$

The constants $ex1$ and $ex2$ represent the exponent of the compressor inlet temperature and speed respectively, and will differ between the compressor groups in accordance with the parameter tuning.

Discharge pressure of the compressors, $p_{d,c}$, is calculated by adding a certain pressure drop (typically two-three bar) to the inlet pressure of the next system component - a compressor, the second compressor stage or a pipeline.

Actual compressor power coefficient:

$$\psi_c = \frac{P_c \times \sqrt{MW_c} \times T_{i,c}^2}{p_{i,c} \times (S_c / 10000)^{3.25}} \tag{14}$$

The speed values in the two last coefficients are divided by 10000 in order to scale the value properly.

According to Figs. 5–9 and 5–10, pressure and power coefficients can be represented as a function of the flow coefficients in accordance with the following equations:

$$\omega_c = b_{1,c} + b_{2,c} \times \varphi_c + b_{3,c} \times \varphi_c^2 \tag{15}$$

$$\psi_c = c_{1,c} + c_{2,c} \times \varphi_c + c_{3,c} \times \varphi_c^2 + c_{4,c} \times \varphi_c^3 \tag{16}$$

The b and c are constants for each compressor found in regression analysis.

The Statpipe and Åsgard sales gas compressors are gas turbine driven. Running the compressors therefore results in CO_2 and NO_X emissions. The amount of emissions subject to taxes, E_{NOX} ([g/s]) and E_{CO2} ([scm/s]), are decided by SFT [54] to be a proportional function of fuel consumption, $Fuel$ ([scm/s]), and can be represented by the following linear equations:

$$Fuel_c = e_{1,c} + e_{2,c} \times P_c \times 1000 \tag{17}$$

$$E_{CO2,\,c} = Fuel_c \tag{18}$$

$$E_{NOX,\,c} = Fuel \times e_{NOX,\,c} \tag{19}$$

There are two different proportionality constants for NO_X emissions, depending on whether the drivers are low-NO_X gas turbines (as for the ÅSG drivers) or not (as for the SGC drivers). The constant $e_{NOX,\,c}$ equals 1.8 g/scm for low-NO_X gas turbines and 16 g/scm for the standard turbines. [54]

Compressor utilisation is limited by a maximum compressor power (related to the maximum available driver power) in addition to minimum and maximum compressor speed.

$$P_c \le P_{c,\,max} \tag{20}$$

$$S_c \le S_{c,\,max} \tag{21}$$

$$S_c \ge S_{c,\,min} \tag{22}$$

The whole compressor station is restricted by a maximum capacity and maximum pipeline inlet pressure.

$$Q_{EuropipeII} + Q_{StatpipeI} \le Q_{Karsto,\,max} \tag{23}$$

$$p_{i,\,EuropipeII} \le p_{i,\,EuropipeII,\,max} \tag{24}$$

$$p_{i,\,StatpipeI} \le p_{i,\,StatpipeI,\,max} \tag{25}$$

In addition, the following constraints regarding relationships between the station components apply for the compressors and connected pipelines of the Kårstø compressor station.

Total flow through the SGC compressors equals the total flow through the BC compressors:

$$N_{SGC} \times Q_{SGC} = N_{BC1} \times Q_{BC1} + N_{BC2} \times Q_{BC2} \tag{26}$$

Flow through each of the BC compressors is directed towards either Statpipe I or Europipe II. The flow rate in Statpipe I is fulfilled by flow from BCI.

$$N_{BC1} \times Q_{BC1} = Q_{StatpipeI} \tag{27}$$

The flow rate in Europipe II is covered from the remaining compressors:

$$\sum_c N_c \times Q_c = Q_{EuropipeII}, c = \{KEP1, \dot{A}SG1, BCII\} \tag{28}$$

For the two-stage compressors, number of stages in operation and flow through the stages are equal for both stage one and stage two.

$$Q_{KEP1} = Q_{KEP2} \tag{29}$$

$$N_{KEP1} = N_{KEP2} \tag{30}$$

$$Q_{\dot{A}SG1} = Q_{\dot{A}SG2} \tag{31}$$

$$N_{\dot{A}SG1} = N_{\dot{A}SG2} \tag{32}$$

Specific power consumption of the whole station is equal to total power consumption divided by the total amount of export gas:

$$\gamma_{Karsto} = \frac{\sum_c N_c \times P_c}{Q_{StatpipeI} + Q_{EuropipeII}} \times 24, \tag{33}$$

$$c = \{SGC, BCI, BCII, KEP1, KEP2, \dot{A}SG1, \dot{A}SG2\}$$

Total compressor station operating cost is related to power consumption and environmental emissions. The costs are divided into four categories:

- Electrical operating costs[3], $Cost_{el}$
- Fuel costs, $Cost_{fuel}$
- CO_2 taxes[4], $Cost_{CO2}$
- NO_X taxes[5], $Cost_{NOX}$

$$Cost_{el} = \sum_c N_c \times P_c \times 1000 \times el, c = \{BC1, BC2, KEP1, KEP2\} \tag{34}$$

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[3] Electricity prices vary throughout the year, but a representative average Norwegian price of EUR 0.06/kWh is used in the calculations.

[4] Based on a current Norwegian tax rate of EUR 0.1/scm CO_2.

[5] Based on a current Norwegian tax rate of EUR 2.0/kg NO_X.

$$Cost_{CO2} = \sum_{c} N_c \times Fuel_c \times 3600 \times t_{CO2}, \ c = \{SGC, \dot{A}SG1, \dot{A}SG2\} \quad (35)$$

$$Cost_{NOX} = \sum_{c} N_c \times E_{NOX, c} \times 3600/1000 \times t_{NOX}, \quad (36)$$

$$c = \{SGC, \dot{A}SG1, \dot{A}SG2\}$$

It is assumed that using fuel gas will not result in any lower present export rate since the fuel gas is taken from the process directly before the gas enters the export compressors and pipelines. Fuel costs are therefore assumed to be zero. However, it is possible to assign a value to the fuel cost in the model.

Total costs for the compressor station are then:

$$Cost_{Karsto} = Cost_{el} + Cost_{CO2} + Cost_{NOX} \quad (37)$$

Optimisation

Optimisation of compressor station operation implies minimising compressor specific power consumption or compressor station operating costs, subject to restrictions in the remaining export system:

Minimise $\gamma_{K\grave{a}rsto}$ or $Cost_{Karsto}$.

5.3.3 Number of compressors in operation

Paper II analyses the effect on specific power consumption by varying operation of export compressor stations. The main variations are the number of compressors in operation (including start-up and shutdown), flow distribution between the compressors, and the use of crossover. Figure 5–11 shows how specific power consumption at the station varies as a function of compressor flow rate and the number of compressors in operation, and for different discharge pressure levels for typical operating conditions. Operating with one compressor at maximum load compared with two compressors in operation at part load reduces specific power conusmption by approximately 25-30%. Operating with two compressors at maximum load can be both more and less energy effeicient than operating with three compressors. This depends on the pressure level.

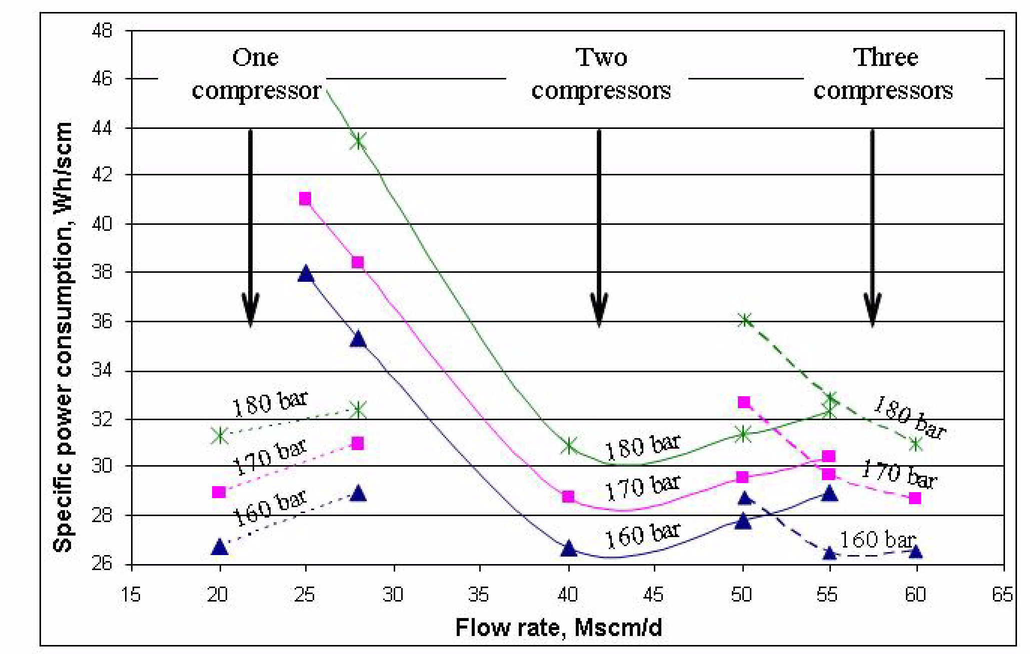

Figure 5–11: Compressor operation impact on specific power consumption

Figure 5–12 shows start-up costs for a compressor[6]. The cost of starting up a new compressor implies that the compressor is operated in recycle mode at minimum governing speed for approximately half an hour. This represents an energy consumption and costs in accordance with the figure.

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6) A representative average Norwegian electricity price of EUR 0.06/kWh is used in the calculations

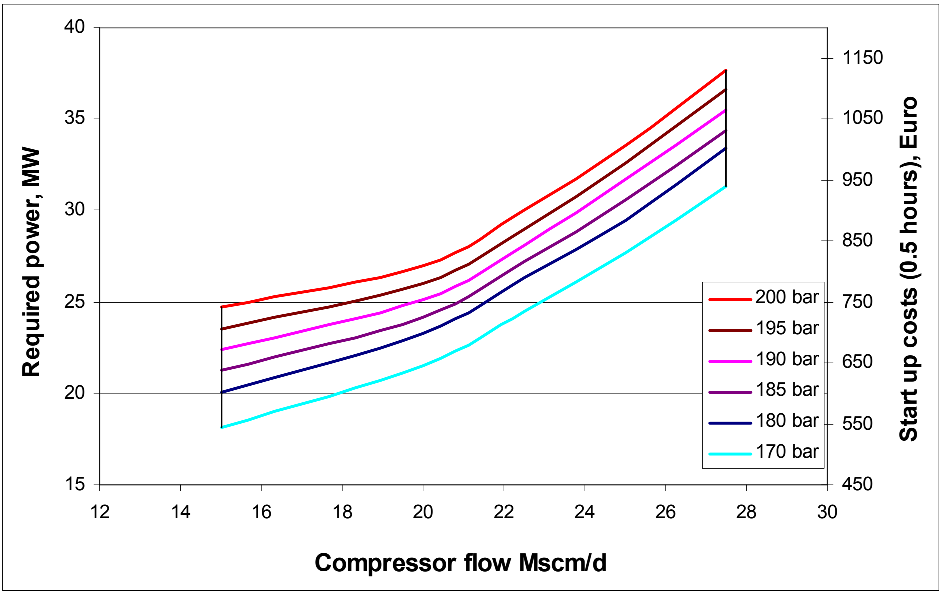

Figure 5–12: Start-up costs for a compressor

5.4 Results from model operation

Tables 5–1 and 5–2 show the effect on power consumption and operational costs of operating in accordance with the established models. In Table 5–1 (extracted from Table 4 in Paper II) the number of compressors in operation and the crossover flow rate in the Kollsnes compressor station are varied for a typical operational case. The difference between the two presented cases amounts to EUR 8438/d or, accumulated up to a year, approximately EUR 3 million. In Table 5–2 (extracted from Table 4 in Paper VI) compressor flow rate distribution between the Åsgard and KEP sales gas compressors at the Kårstø compressor station is varied. Decreasing flow rate in the electrically-driven KEP compressor and increasing flow rates through the gas turbine-driven Åsgard compressors increases daily power consumption by 71 MWh. This corresponds to an annual increase of approximately 26 000 MWh. However, the operating cost is reduced by EUR 6 816/d, corresponding to approximately EUR 2.5 million/year.

Table 5–1: Effects of varying operation at the Kollsnes compressor station

Flow rate, Mscm/d			Power consumption		Costs
Zeepipe IIA	Zeepipe IIB	Total			
65	70	135	Wh/scm	MWh/d	EUR/d
6 compressors, without crossover			31.2	4210	263 250
5 compressors and crossover			32.2	4342	271 688
Difference			1.0	132	8 438

Table 5–2: Effects of varying operation at Kårstø compressor station

Flow rate, Mscm/d		Åsgard/KEP Sales gas compressors						Kårstø compressor station		
Statpipe I	Europipe II	Number		Flow, Mscm/d		Speed, rpm		Power consumption		Costs
5	54.3	KEP	Åsg	KEP	Åsg	KEP	Åsg	Wh/scm	MWh/d	EUR/d
Case 1		1	2	21.1	16.6	6294	8744	27.70	1984	84648
Case 2		1	2	13.8	20.3	6035	9494	28.16	2055	77832
Difference								0.46	71	-6816

Table 5–3 shows the effect on Kollsnes power consumption of including a degraded compressor in the station. The established optimisation model for Kollsnes is used on a typical operational case implying a total flow rate from Kollsnes of 125.4 Mscm/d and a slightly higher pipeline pressure in Zeepipe IIA than IIB. Optimum operation in the design case refers to six equally modelled compressors at the station. Optimum operation with one degraded compressor implies that one of the compressors directed towards Zeepipe IIB is replaced by a degraded modelled compressor. Compressor station operation for this case is optimised and compared with design operation. Furthermore, this is compared with operating in accordance with design operation (with flow rates equally distributed between the three compressors directed towards Zeepipe IIB), but with one of the compressors modelled as degraded. Optimum operation with one degraded compressor at the station increases operational costs by EUR 2 040/d (EUR 745 000/year). Design operation with one degraded compressor increases operational costs by EUR 2 400/d (EUR 876 000/year) compared with the design case.

Table 5–3: Effects of a degraded compressor at the Kollsnes compressor station

		Towards Zeepipe IIA			Towards Zeepipe IIB					Power consumption		Costs
					Design			Degraded				
		Number	Flow, Mscm/d	Speed, rpm	Number	Flow, Mscm/d	Speed, rpm	Flow, Mscm/d	Speed, rpm	Wh/scm	MWh/d	EUR/d
Design	Optimum operation	3	20.8	6087	3	21.0	6057	-	-	29.19	3660	219648
1 degraded compressor	Optimum operation	3	21.1	6114	2	21.6	6067	19	6012	29.47	3696	221688
	Design operation	3	20.8	6087	2	21.0	6057	21	6084	29.51	3701	222048
Difference from design	1 degraded compressor and optimum operation									0.28	36	2040
	1 degraded compressor and design operation									0.32	41	2400

5.5 Discussion

Figures 5–9 and 5–10 show that conformity between the fitted line from the regression analysis for compressor discharge pressure and power and the data point from the simulation is sufficient for the analysis purpose. The deviation is below 4% for all simulated data. Actual compressors will seldom operate exactly as designed. Figures 5–9 and 5–10 also display the differences between historical operational data and the established equations for compressor discharge pressure and power respectively. The differences are well below 4% for all cases with regard to the equation for pressure coefficient and for most cases (75%) with regard to the equation for power coefficient. The established equations therefore describe compressor performance satisfactorily.

The number of compressors in operation, flow distribution between them and use of the crossover leg are proven to have the highest effect on compressor specific power consumption and operational costs. Analysis of these effects for some typical operational cases shows that the difference in costs may add up to EUR 3 million/year for a compressor station. In extreme cases, the number may also be higher.

Running the established models for more cases shows that equally distributed gas flow between equal compressors directed towards the same pipeline and approximately equally distributed gas flow between intermediate pipelines connected to the compressor station will provide the most energy efficient operation. Using the crossover leg at Kollsnes represent losses, and will only be efficient when one of the compressors is inoperative. Starting up a compressor in order to operate in accordance with the desired operation implies start-up costs. However, these costs will be recovered within a maximum of 15 hours, compared with inefficient operation with one less compressor and the potential use of the crossover leg.

Varying flow distribution at the Kårstø compressor station boots costs, but cuts power consumption by increasing the flow rate through the electrically-driven KEP compressor. This is because of the relative estimate of emission costs for gas turbines compared with electricity costs for electric motors, since the station comprises both electrically-driven compressors and gas turbine-driven compressors.

In Paper II, the effects on energy efficiency if a compressor is degraded are analysed. Figure 7 in the paper shows how power consumption increases and the optimum operation point with regard to flow rate changes for a degraded compressor. The results presented above support this analysis, and show how optimum operation implies decreasing flow rate through the degraded compressor with approximately 10% while increasing flow rates in the other compressors. Taking into no account of a compressor being degraded and operating as normal will fail to achieve the most energy-efficient operation of the compressor station. However, the difference is relatively small.

The analysis and models described in this chapter may also serve as a tool for enhancing understanding between operators of the compressor stations and the export system operator.

Gas composition affects the overall performance of compressor units. Operating with different gas compositions from different suppliers is not uncommon, nor is the exposure to gas quality changes whenever contingencies arise in the gas processing plants. Different gas compositions influence compressor efficiency, temperature and pressure increase. At the Kollsnes export compressor station, gas arrives from the Kvitebjørn, Visund and Troll fields. Deliveries from Visund and Kvitebjørn have a higher molecular weight than gas from Troll, and are processed separately before compression. Gas from all four processing trains is delivered into the same compressor suction model and mixed in this. However, the compressors nearest the processing train for Visund and Kvitebjørn will receive gas with a different gas composition and temperature. This affects compressor flow distribution and optimum compressor station operation, and should be taken into account when optimising operation. Eriksen [24] has developed a model which calculates the gas composition and inlet temperature of each compressor, depending on the amount of gas from Visund, Kvitebjørn and Troll respectively, and on how many and which compressors are in operation. This model should be integrated with the compressor station operation established in this work.

The next chapter deals with optimum export system operation, where the established compressor station models presented in this chapter will be included.

5.6 Conclusion

This chapter supports objective C by establishing models for optimum operation of gas export compressors in the system. Paper III presents a mathematical model established for operating the Kollsnes export compressor station. This chapter has presented the mathematical model for operating the Kårstø compressor station. Applying these models makes it possible to analyse the effects of varying operation of the compressor stations and to find the most energy and environmentally efficient mode of operation.

Several different ways to operate the compressor stations are available. Each of these may be equal in terms of meeting system requirements, but may differ in terms of energy efficiency. Paper II analyses the effects on specific power consumption by varying compressor operation. One compressor at full load is more energy efficient than two compressors at part load in recycle. However, an extra compressor in operation is more energy efficient than the minimum number as long as this does not imply operating the compressors in recycle. Equally distributed gas flow between compressors and intermediate pipelines is found to be the most energy-efficient mode of operation. However, when a compressor at the station is degraded, optimum operation implies decreasing flow rate through this compressor while increasing flow rates in the other compressors. Furthermore, the crossover leg at Kollsnes should in general only be used when one of the compressors is inoperative. Beyond that, starting up a new compressor will be more energy efficient than using the crossover leg. The study concludes that energy and costs savings will be obtained by operating the compressor station in the most efficient way.

6 Optimum operation of gas export systems

6.1 Introduction

The purpose of this chapter is to establish an optimisation model for optimum operation of gas export systems. It contains the background and theoretical foundation for Paper III and supports objective D. The established model is based on the models and methods presented in chapters 4 and 5. The chapter furthermore presents results from running the model, validation of the model and comparison with actual system operating data (described in Paper VI). The main results and conclusions from Paper III and in part Paper VI are presented and discussed.

Operating gas export systems efficiently calls for detailed knowledge of system integration and the relationships between customer nominations, pipeline flow and inventory, compressor station operation and operational flexibility of the system. It means more than optimum operation of system components (such as export pipelines and compressor stations) separately. All system components must also operate optimally together, which may imply that some system components cannot operate in their most efficient way. Optimum operation requires striking a delicate balance between high operational flexibility and associated high pipeline pressures and energy consumption on the one hand, and lower pressure and energy consumption with the risk of losing gas sales on the other.

Traditional methods for deciding how a system should be operated rely on knowledge and expertise to select stations and flow routing manually in order to achieve the best and safest operation. The method primarily considers security of supply and to a lesser degree the economic and environmental issues related to energy efficiency. Simulation with trial and error is common, but this will limit the time available to experiment with different what-if scenarios and to manipulate the system to find improvements. An exhaustive number of alternatives to simulate also exist, but only a limited number of cases can be selected for simulation. Discretisation is necessary, and this results in a tiny portion of the alternatives to be tried. But this portion may not comprise the best solution. Optimising of system operation will generally provide a better, faster and more efficient way to identify the most energy-efficient mode of operation.

Optimising is the process of selecting the best solution from multiple alternatives. For operation of gas export systems, the focus is on minimising energy consumption and environmental emissions by selecting the best combinations of compressor units and stations to run with flow distribution in the units and in the pipelines, and the ideal level of pipelines inventories for a given set of operating conditions and nominations to be fulfilled.

6.2 Theoretical foundation and research procedure

6.2.1 System relationships, and routines and procedures for system operation

An optimisation model of gas export system operation will be developed by combining the models and methods for optimum pipeline inventory and operation of compressor stations (presented in chapters 4 and 5). In addition, actual physical and operational relationships between the system components will be included. These are found in the formal description of the gas export system and its capacities at the system operator (Gassco) [27] and from the operator's operational experiences. Operation of the system is strongly related to customer nominations and capacity booking. The basic routines and procedures related to technical and economical aspects of gas transport and for communication between shippers and gas export system operator (Gassco) are described in the Shipper Manual [26]. Routines for booking capacity are described in the Booking Manual [28]. Appendix H presents an extract of these routines and procedures.

6.2.2 Operations research and optimisation theory

According to Domschke and Drexl [22], operations research (OR) is a method which should be used as preparation in a decision process. Strategic and operational planning with OR comprises six steps:

- identification and analysis of the problem
- identification of the objective and possible solution approaches
- formulation of a mathematical model
- obtaining necessary data
- solving the problem by utilising the mathematical model and the collected data
- evaluation of the solution(s).

Identification of the problem, objective and solution approaches are presented in chapters 1 and 2. Formulation of the mathematical model is presented in this chapter as well as in chapters 4 and 5. Furthermore, this chapter presents necessary data and the results by utilising the established model. Evaluation of the solution(s) is presented in this and the next chapter.

A model is a simplified picture of a real system. An optimisation model is a formal representation of a planning or decision problem which consists of three fundamental elements:

- The objective function - the function to be minimised or maximised.
- The control (decision) variables - the variables in the problem which can be manipulated to achieve the objective.
- The constraints - all equations and parameters which mathematically model the system. The constraints may be both inequalities and equalities.

In this work, a variable is defined as an attribute of a system or a process which may change its value during the course of its observation across samples or during the operation of a system. When modelling, variables are distinct from parameters, which are kept constant during a simulation, calculation or similar. A parameter is a quantity which defines certain characteristics of systems or functions. The function or system may then be re-evaluated or reprocessed with different parameters to give a function or system with different behaviour. The term “properties” includes both variables and parameters.

The mathematical algorithm formulated in this work consists of more non-linear equations. Therefore, solving the optimisation model must make use of non-linear optimisation methods. In a general form, the non-linear programming problem is to find $\mathbf{x} = (x_1, x_2, \ldots, x_n)$, so as to:

$$\text{Minimise } f(\mathbf{x}),$$

subject to

$$g_i(\boldsymbol{x}) \le b_i, \text{ for i=1,2,...,m},$$

and

$$\boldsymbol{x} \ge 0,$$

where f(**x**) and $g_i(\boldsymbol{x})$ are given functions of the n decision variables, the decision variables, **x**, are real, continuos numbers and m is the number of constraints.

No algorithm able to solve every specific problem fitting this format is available, so different methods exist to solve such problems exist. The mathematical model formulated in this work is a constrained non-linear optimisation problem, implemented in Matlab[1] and in Excel[2]. The problem is solved by using the Karush-Kuhn-Tucker (KKT) conditions. These are necessary conditions which an optimum solution of such a problem must satisfy. The KKT conditions are embodied in the following theorem [34]:

Assume that f(**x**) and $g_i(\boldsymbol{x})$ (i=1..m) are differentiable functions (satisfying certain regularity conditions), then

$$\boldsymbol{x}^* = (x^*_1, x^*_2, \ldots, x^*_n)$$

can be an optimal solution for the non-linear problem only if there exist m numbers $u_1, u_2, \ldots, u_m$ such that all the following KKT conditions are satisfied:

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1) Matlab is a trademark of the MathWorks Inc.
2) Excel is a trademark of Microsoft Corporation.

1. $\frac{\partial f}{\partial x_j} - \sum_{i=1}^{m} u_i \times \frac{\partial g_i}{\partial x_j} \le 0$, at $\boldsymbol{x} = \boldsymbol{x}^*$, for $j = 1, 2, \ldots, n$
2. $x^*_j \times \left(\frac{\partial f}{\partial x_j} - \sum_{i=1}^{m} u_i \times \frac{\partial g_i}{\partial x_j} \right) = 0$, at $\boldsymbol{x} = \boldsymbol{x}^*$, for $j = 1, 2, \ldots, n$
3. $g_i(\boldsymbol{x}^*) - b_i \le 0$, for $i = 1, 2, \ldots, m$
4. $u_i \times [g_i(\boldsymbol{x}^*) - b_i] = 0$, for $i = 1, 2, \ldots, m$
5. $x_j^* \ge 0$, for $j = 1, 2, \ldots, n$
6. $u_i \ge 0$, for $i = 1, 2, \ldots, m$

However, satisfying these conditions does not guarantee that the solution is optimal. To ensure a global minimum, then f(**x**) and $g_i(\boldsymbol{x})$ also need to be convex functions.

6.2.3 System operating data

System operating data from the past two-three years have been collected and systemised. They are used to find a representative gas flow constant, k, in the gas flow equation, Eq. (3) (see Paper VI). Furthermore, the data are used to find typical operational cases for running the model, and for validating the model and comparing its result with actual operation.

6.3 The optimisation model

Detailed description of the mathematical optimisation model and the equations comprising the model can be found in Paper III and chapter 5. The system operation is modelled as steady state. This section gives a brief description of it.

Input variables to the model is:
- customer nominations at all exit terminals
- production rates on all producing fields.

In addition, the following constraint parameters must be specified:
- different coefficients (from regression analyses)
- exponents in performance equations
- pressure drop across platforms and between system components
- gas flow constants
- maximum and minimum capacities and limits
- molecular weights
- compressor inlet temperatures
- compressor inlet pressures
- prices of fuel and electricity, and emission taxes.

The following constraints are modelled:

- flow balances and flow routing
- export pipeline pressures (as described in chapter 4)
- pressure drops across platforms and compressor stations
- relationships between flow and pressures in intermediate pipelines
- maximum and minimum capacity restrictions
- compressor performance coefficients
- fuel consumption and amount of emissions
- cost calculations.

The following control variables will be varied in the optimisation:

- compressor speed (influencing compressor and intermediate pipeline pressures)
- number of compressors in use
- flow distribution and routing in compressor stations and in the system (including flow rate in crossover legs).

Figure 6–1 shows a schematic illustration of the optimisation model, its input, output and control variables. The model itself is illustrated as a box which comprises all the mathematical model equations (constraints) as well as the objective function.

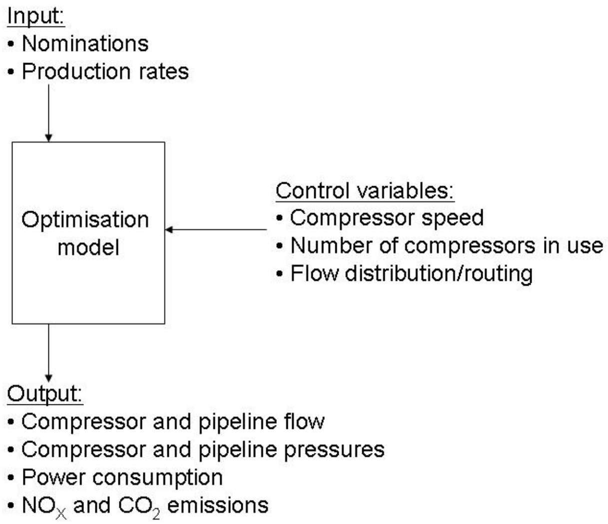

Figure 6–1: Schematic illustration of the optimisation model

In the optimisation of system operation two different independent objective function can be minimised (but only one at a time) - either system specific power consumption:

$$\text{Minimise } \gamma_{tot}$$

or total system operating costs:

$$\text{Minimise } Cost_{tot}$$

6.4 Model results

By analysing the optimisation model results for certain input data at a specific day, optimum operation for this day will be found with regard to either minimum system power consumption or operating costs. Paper VI presents several results from this analysis for different cases, and from varying certain variables, and compares the results with actual operation. An extract from the results is presented in the following.

Optimising of the system should provide more energy and environmentally efficient operation of the system than actual operation. To verify this, model results are compared with actual operating data. Table 6–1 presents a comparison for one specific day.

Table 6–1: Comparison between model results and actual operating data

	Export pipelines			Intermediate pipelines							Specific system power consumption, Wh/scm
	Franpipe	Zeepipe	Europipe II	Zeepipe IIA			Zeepipe IIB			Statpipe I	
	Inlet pressure, bar	Inlet pressure, bar	Inlet pressure, bar	Inlet pressure, bar	Flow, Mscm/d	Number of compressors	Inlet pressure, bar	Flow, Mscm/d	Number of compressors	Inlet pressure, bar	
Actual	147.0	136.0	182.0	186.0	70.0	3	181.0	55.0	2	149.0	33.93
Model	144.4	138.4	186.6	177.1	60.8	3	185.6	64.5	3	126.2	32.50

The difference in specific power consumption is 1.43 Wh/scm. For this specific day, that equals a daily difference in power consumption of 222 MWh.

In Table 6–1, the flow from Kårstø towards Draupner (Statpipe I) is fixed, so that total flow from Kårstø and Kollsnes respectively will be the same as for the actual historical day. Table 6–2 presents the effect on system specific power consumption and system operating costs of varying the flow rate in Statpipe I, and thereby flow rates from Kollsnes and Kårstø respectively.

Table 6–2: Effects of varying flow rate in Statpipe I in the model

	Intermediate pipelines			System operating costs, EUR/scm	Specific system power consumption, Wh/scm
	Zeepipe IIA	Zeepipe IIB	Statpipe I		
	Flow, Mscm/d	Flow, Mscm/d	Flow, Mscm/d		
Base case I	60.8	64.5	4.7	0.001703	32.50
Varying flow rate	63.0	67.0	0.0	0.001705	32.40
	66.7	53.3	10.0	0.001690	32.81

By reducing the flow rate in Statpipe I compared to the base case, specific power consumption decreases by 0.10 Wh/scm, but system operating costs increase by EUR 0.2e-5/scm. This corresponds to a daily difference of only 16 MWh and EUR 310 respectively. By increasing the flow rate in Statpipe I, specific power consumption increases while system operating costs decreases.

In Table 6–1 the crossover flow rate in the crossover leg at the Kollsnes export compressor station equals zero. Table 6–3 presents the effect on system specific power consumption and system operating costs by varying the crossover flow rate and the number of compressors in operation at the Kollsnes compressor station.

Table 6–3: Effects of varying crossover flow rate at Kollsnes in the model

	Zeepipe IIA			Zeepipe IIB			Crossover flow rate, Mscm/d	System operating costs, EUR/scm	Specific system power consumption, Wh/scm
	Flow, Mscm/d	Number of compressors	Compressor flow rate, Mscm/d	Flow, Mscm/d	Number of compressors	Compressor flow rate, Mscm/d			
Base case II	61.5	3	20.5	61.5	3	20.5	0.0	0.001771	33.59
Varying flow rate	60.7	2	26.4	62.3	3	23.4	8.0	0.001786	33.84

Increasing the flow rate in the crossover leg compared with the base case boosts system specific power consumption by 0.25 Wh/scm, while operating costs rise by EUR 2.0e-5/scm. This corresponds to a daily difference of 39 MWh and EUR 2 325 respectively.

Since the two established objective functions are independent, optimum system operation may differ depending on which of the objective functions is applied. Table 6–4 compares the results of minimising system operating costs with minimisation of system specific power consumption. The only variations for this case will be the flow distribution at the Kårstø export compressor station (because the flow rate in Statpipe I is fixed). Table 6–4 therefore shows only operation of compressors at this station.

Table 6–4: Comparison between minimisation of operating costs and specific power consumption

	Åsgard/KEP Sales gas compressors						System operating costs, EUR/scm	System specific power consumption, Wh/scm
	Number		Flow, Mscm/d		Speed, rpm			
	KEP	Åsg	KEP	Åsg	KEP	Åsg		
Power minimisation	1	2	21.1	16.6	6294	8744	0.001441	27.70
Cost minimisation	1	2	13.8	20.3	6035	9494	0.001396	28.16

6.5 Discussion

The cases presented above and the additional cases presented in Paper VI show that varying system pressures and flow distribution for the same customer nominations influences and changes system specific power consumption and operating costs. Using the model will provide the most favourable system operation and increase energy and environmental efficiency compared with actual operation. Accumulated up to a year, the difference presented in Table 6–1 equals approximately 81 000 MWh. If the energy price is set equal to the price of electricity, this adds up to almost EUR 5 million per year. Since some of the compressors are gas turbine-driven, and do not use electricity, this is not completely true. That is discussed later. However, the electricity price will be a representative cost for energy.

The most important trends for differences between model results and actual historical operation can be identified from Table 6–1 as:

- The model recommends almost equal flow rates in Zeepipe IIA and IIB when the same number of compressors is directed to each of these two intermediate pipelines. However, the actual operational data show that this is not always the case.
- Recommended inlet pressure of export pipelines is generally almost equal to actual inlet pressure values for high pipeline capacity utilisation.

- Pressures of intermediate pipelines are often lower in the model than in the actual historical data. (This can also be identified in Fig. 4–2)

More efficient flow distribution and lower pipeline pressures leads to lower system power consumption.

Table 6–2 shows that reduced flow rates in Statpipe I may reduce system specific power consumption but increase system operating costs compared with the base case. Increased flow rate boosts specific power consumption and reduces specific operating costs. Whether optimum operation implies reduced or increased flow will depend on the minimisation objective, and also on the total flow rate in the system, customer nominations at each respective exit terminal, and the number of operative compressors. Nevertheless, the possibility of varying the Statpipe I flow rate in the model enhances opportunities for operating all system compressors as close to their optimum ranges as possible and improves operational flexibility.

The model will mostly recommend a zero flow rate as the optimum value through the crossover leg at Kollsnes, as in base case II in Table 6–3. Specific power consumption and operating costs are then lower than from using the crossover leg, as also discussed in chapter 5. The model recommends instead using the opportunity to send gas from Sleipner towards Draupner (See Fig. 3–1) to achieve the right flow distribution in the export pipelines. The reason for this is that using the crossover leg results in an unwanted pressure loss between the two intermediate pipelines connected to Kollsnes. In some cases, however, including both crossover opportunities at Kollsnes and variable flow rates in Statpipe I could reduce system operating costs and specific power consumption. This is because the flow rate from Kollsnes may be reduced and less compressors needed if the flow rate from Kårstø and through Statpipe I can be increased efficiently. However, the opportunity to use the crossover and optimise the crossover flow rate is important in cases where one of the six compressors at Kollsnes is not in operation.

Table 6–4 shows that flow distribution at the Kårstø gas treatment plant is slightly changed when system operating costs rather than specific power consumption are minimised. Minimising system operating costs increases the flow rate up to the maximum level in the gas turbine-driven compressors (the Åsgard compressors in the case presented in Table 6–4), and accordingly decreases through the electrically-driven compressor (the KEP compressor in the case presented). These changes in optimum operation reflect the assessed prices of electrical energy compared with the assessed prices of emissions. These values are uncertain and variable, however, and optimum operation based on minimising system costs is consequently sensitive to variations in these parameters. A sensitivity analysis of varying these parameters is presented in next chapter.

In addition to finding optimum operation of the system, using the model provides the system operator with information on the most energy-efficient way to operate subsystems (such as the compressor stations) for given customer nominations. Based on this knowledge, the system operator can adjust the nomination instructions it gives to subsystem operators compared with the original plan, and utilise flow routing flexibility elsewhere in the system to fulfill customer nominations. Using the model may also be part of forecasting analyses, and it can provide better information on the consequences of being able to deliver with increases in nominations and unexpected shutdowns, as presented in section 4.3.2.

The model results will provide detailed recommendations on flow rates, pressures and compressor operation for a specific case. Before putting the recommendations into operation, however, they must be evaluated by the system operator for the specific case. Special circumstances or conditions may result in additional restrictions for a specific operational case. For instance, the various customer sales contracts specify the allowable range of energy content, GCV and WI, together with water, sulphur, CO_2 and H_2S content. Some of the producing fields may deliver gas with properties outside these ranges. This may limit the operational flexibility of the system. Commingling of gas streams will in those cases be necessary to fulfil the contractual commitments.

The established optimisation model is for steady state conditions, but pipelines are rarely run in a steady state. However, a transient model will have many more variables and be very complex and time consuming to solve. In addition, nominations are made on a daily basis. It is therefore assumed that steady state assumptions are representative. Although the model is steady state, it is based to some extent on transient conditions. The recommended inventory curves are established by take account of potential increases in customer nominations and immediate shutdowns of equipment, which are transient situations. In section 4.3.2, the model for pipeline inventory is validated for such transient conditions.

However, validation of the inventory levels showed that in some cases the recommended inventory might be too low. Should the system operator want a higher delivery security, the recommended inventory levels can nevertheless be modified and increased. This will result in higher pressures, but the system optimisation model will still find the most energy-efficient operation of the system for given customer nominations and the desired inventory levels.

Enhanced or amended in environmental requirements may change the focus for optimum system operation. Fulfilling customer nomination is currently the most important job for the system operator. However, the greatly increased attention being paid on climate change and environmental emissions may alter this more towards minimising of power consumption and environmental emissions, even though this may also lead to increased shortfalls.

The next chapter deals with an analysis which weighs the benefits of operating in accordance with the established model against its costs. It also includes a sensitivity analysis which varies key parameters and variables in the model and examines the impact on total benefits and costs. These analysis will be followed by the development of guidelines and visual displays which will be implemented in strategic planning and actual operation of the system.

6.6 Conclusion

This chapter supports objective D by establishing a model for technically and economically optimum operation of a gas export system. A major challenge operating such systems is to operate at minimum cost and with minimum environmental emissions while fulfilling variations in contractual nominations and maintaining sufficient pipeline inventory to provide operational flexibility. Paper III analyses system integration which forms the basis for the system optimisation model, and describes the main part of the optimisation model for energy-efficient operation of the system. The model is established by combining knowledge of system integration with the models on optimum inventory and compressor station operation. The model minimises specific power consumption or total system operating costs, while maintaining operational flexibility. Minimising one or the other may yield two different results for system operation.

The model is validated and it represent the actual export system to a confidence level. Analysing the model results confirms that energy savings can be obtained by operating the gas export system in accordance with the model. Furthermore, the model provides the system operator with information on energy efficient operation of subsystems which the system operator can use to adapt nomination instructions to subsystem operators.

7 Cost-benefit analysis

7.1 Introduction

The focus in this chapter is on presenting a cost-benefit analysis (CBA) of the operation of gas export systems, including a sensitivity analysis of variations in key operationa variables and parameters (key properties). The chapter supports objective E. Its purpose is to analyse whether operating the NDGES in accordance with the established model will provide a positive net value, and whether this value is better than the net value of current operation. The chapter contains background information for, and the main results and conclusions from, the CBA presented in Papers III and V. Further development of the CBA, a thorough sensitivity analysis, numerical cases and discussion of the results follow in this chapter. This study utilises the CBA concepts, practices and principles presented in Boardman et al. [7] and in *Guide in socio-economic analyses* [47].

A CBA is a useful tool for decision-making. It considers all the costs and benefits to society as a whole, and not just a single enterprise. The intention of the analysis is to clarify and systematise the economic and environmental consequences of different actions before a decision is taken. It offers a basis for evaluating the profitability of an action and for ranking different options. The analysis is used to ensure a positive net value which means that the expected net benefits from initiating an action are greater than the costs involved, and that the option with the higest net value is chosen. This work will compare operation in accordance with the established optimisation model with current operation and with maximum pipeline inventory operation.

Chapter 6 has confirmed that operating in accordance with the optimisation model reduces system operating costs and power consumption compared with current operation. These cost savings equals the benefits of changing operation. The CBA will evaluate these benefits against expected increase in costs from operating in accordance with the model, which is found to be the cost of potential lost gas sales.

A CBA requires a prediction of the future. Uncertainty will exist about the magnitude of the predicted impacts and the values assigned to the parameters. Basic analyses usually submerge this by using the most plausible estimates of the unknown quantities. Sensitivity analysis is a way of evaluating how sensitive the costs and benefits are to variations in key properties. Moreover, the purpose is to determine how net value changes if these properties deviate from their assumed values. The result of a CBA may be heavily dependent on the values such properties take.

7.2 Theoretical foundation

7.2.1 Steps in a CBA

The major steps in a CBA are described in Papers III and V, and summarised and illustrated in Fig. 7–1.

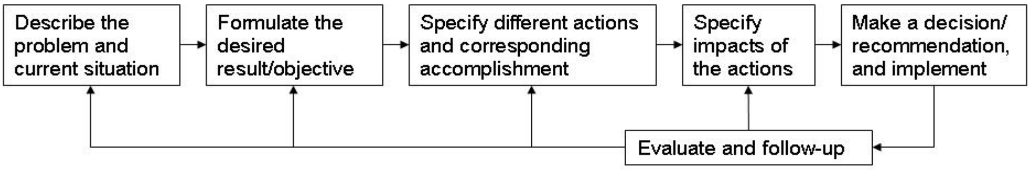

Figure 7–1: The process of a cost-benefit analysis

7.2.2 Sensitivity analysis

Boardman et al [7] suggest three approaches on how to perform a sensitivity analysis: partial sensitivity analysis, worst- and best-case analysis, and Monte Carlo analysis.

According to [7], partial sensitivity analysis is the most commonly used approach. It focuses attention on how net value changes as one single variable or parameter is varied while holding all others constant. The marginal partial effect of changes in probability on net value is thereby isolated. Inspection of partial sensitivity graphs generally gives a good indication of the nature of the relationship.

Extreme-case analysis (worst/best) examines whether combinations of plausible assumptions exist that reverse the original sign of net value. The base-case assumptions, which generally assign the most plausible numerical values to unknown properties, produce an estimate of net value which is thought to be most representative. A plausible lower bound on net value can be found by considering the least favourable of the plausible range of values for each parameter and variable. In this way, a pessimistic prediction of net value may be calculated. The same applies for an optimistic prediction. If the ranges are plausible, however, the probability of actually realising the extreme net value gets very small as the number of parameters and variables becomes large.

The sensitivity analysis presented in this chapter will use a partial analysis, which will apply the plausible extreme values of each key property and analyse the effects.

Partial- and extreme-case sensitivity analyses have two major limitations. First, they may not take into account all available information about the assumed value of variables and parameters. In particular, if values near the base-case assumptions are more likely to occur than values near the extremes of their plausible ranges, the extreme cases are highly unlikely to occur because they require joint occurrence of a large number of independent low-probability events. Second, these techniques do not directly provide information about the variance, or spread, of the statistical distribution of realised net value.

Monte Carlo analysis provides a way of overcoming these problems. This attempts to estimate the distribution of net value by explicitly treating assumed property values as random variables (i.e, as draws from probability distributions). The distribution of net value is commonly represented by a histogram. This provides a visual display of the entire distribution of net values so that its spread and symmetry can be detected. The trials themselves can be used to calculate the sample variance. Monte Carlo analysis is not carried out in this study. It would make the sensitivity analysis much more complex and time-consuming. In addition, Monte Carlo analysis assumes in part that it is possible to determine the distribution of each variable and parameter. A thorough analysis to decide these distributions would then be necessary, but would in itself imply uncertainty and be difficult to perform.

7.3 Results from the CBA

The first steps in the CBA (illustrated in Fig. 7–1) are described more thoroughly in Paper III (and V). Calculations of the costs and benefits of each evaluated action and the sensitivity analysis are presented in detail in this chapter.

7.3.1 Problem definition and main objective

The CBA starts with a description of the problem and the goal of initiating actions. The main objective was identified to be establishing a more energy-efficient way to operate the gas export system so that:

- power consumption and environmental emissions are minimised - energy efficiency
- customer nominations are fulfilled - delivery security.

7.3.2 Actions

In this work, three actions have been considered and compared with regard to costs and benefits.

- Operating in accordance with the established system optimisation model
- Continuing to operate along the present lines (current operation)
- Operating at maximum export pipeline inventories (designated maximum operation)

The first action implies operating the export pipelines in accordance with the established recommended inventory curves and using the established system optimisation model. Current operation, the second case, means either applying actual historical operating data or typical trends in actual operation. The third action implies applying the established mathematical algorithm (the model) for system operation, but operating the export pipelines at maximum inventories for given flow rates. (See Fig. 4–2). Compressor operation is optimised in accordance with these inventory levels.

7.3.3 Impacts - costs and benefits

The main costs from changing the operation of the gas export system are identified as shortfall costs. These represent the cost of buying gas in the short term market, the cost of lost reputation, and the potential cost of gas lost to the customers.

The main benefits from changing the operation of a gas export system are identified as:

- reduced operating costs for electrically-driven compressors
- reduced emissions
- reduced operating costs for gas turbine-driven compressor

- reduced maintenance costs.

7.3.4 Numerical cases and recommendations

The following two numerical cases, for two different system capacity utilisations, will calculate costs and benefits for the various actions specified above. These calculations are based on the prices presented in Table 7–1. Fuel costs are assumed to be zero and maintenance costs are neglected as discussed in Paper III.

Table 7–1: Base prices for energy and emissions

Short term gas price	EUR/scm	0.16
Electricity price	EUR/kWh	0.06
CO_2 tax	EUR/scm fuel gas	0.10
NO_X tax	EUR/kg NO_X	2.00

Case 1, the base case, is an analysis based on average exit terminal nominations (over the past two years), and equals approximately 80% system capacity utilisation[1]. The case is based on a specific day referred to as Week IV in Paper VI. The established optimisation model is run for this specific day, and model results are compared with actual operation and maximum operation. Table 7–2 shows the base data for Case 1, and Table 7–3 presents the main differences in operating data.

Table 7–2: Flow rate data for Case 1 - 80% capacity utilisation

Total nomination	Mscm/d	267
Total export from Kollsnes	Mscm/d	123
Total export from Kårstø	Mscm/d	75
Total production from other fields	Mscm/d	69

Table 7–3: Pipeline operating data for the three alternative actions in Case 1

		Optimisation model	Actual operation	Maximum operation
Pressure, Zeepipe IIA	bar	186	181	187
Pressure, Zeepipe IIB	bar	188	193	190
Pressure, Statpipe I	bar	134	146	136
Pressure, EuropipeII	bar	185	185	187
Flow rate, Zeepipe IIA	Mscm/d	61.5	57.0	61.5
Flow rate, Zeepipe IIB	Mscm/d	61.5	66.0	61.5
Number of compressors, IIA		3	2	3
Number of compressors, IIB		3	3	3

Table 7–4 presents and quantifies the costs and benefits of operating in accordance with the optimisation model compared with current and maximum operation. Total system

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1) System capacity utilisation implies relating export pipeline flow rates to maximum pipeline flow rates.

operating costs are minimised in the optimisation, and the results are accumulated up to a year.

The first column in the table shows total power consumption and environmental emissions from operating in accordance with the model. This results in a specific power consumption of 33.82 Wh/scm and a specific cost of EUR 1 765/Mscm of export gas. It should be noted that this cost is only one hundredth of the short term gas price of EUR 0.16/scm (equal to EUR 160 000/Mscm). Furthermore, no shortfalls are expected from operating in accordance with the model. This assumption is based on the consequence analysis in section 4.3.2. The analysis showed that operating in accordance with recommendations at 80% capacity utilisation implies enough inventory to avoid shortfalls.

The two next columns compare the model results with actual operating data for differences in quantity and cost. In the actual data from this specific day, utilisation was greater for electrically-driven compressors and smaller for gas turbine-driven compressors than in the model. This results in higher electricity costs and lower emission costs in the actual operating data. However, operating in accordance with the model yields a net cost reduction (benefit) of EUR 5 576 846/year. The calculated amount of shortfalls in actual operation is based on the historical deliverability of approximately 99.8% and total dry gas exports from the NCS of 86.2 billion scm in 2006. This results in a relative large decrease in shortfall costs from operating in accordance with the model compared with actual operation. This is further discussed below.

The last two columns compare the model results with maximum operation. No differences exist in shortfall costs between those two actions, since no shortfalls are expected. Maximum operation implies higher pipeline inventories and pressures, and thereby higher operating costs. Therefore, operating in accordance with the optimisation model yields a positive net value compared with maximum operation.

Table 7–4: Costs and benefits for Case 1 from optimised system operation

		Model results versus			
		actual operation		**maximum operation**	
	Model results	**Cost reduction (benefit)**		**Cost reduction (benefit)**	
		Quantity	**Value, EUR/year**	**Quantity**	**Value, EUR/year**
Power consumption of electric motors, Kollsnes, kW	150 521	11 429	6 006 951	1 538	808 110
Power consumption of electric motors, Kårstø, kW	42 051	1 617	849 895	1 083	569 225
Power consumption of gas turbines, Kårstø, kW	86 731	-4 742	0	236	0
CO_2 emissions, Kårstø, Mscm/year	230	-10	-980 000	1	50 000
NO_X emissions, Kårstø, tonnes/year	1 748	-150	-300 000	8	16 000
Sum benefits, EUR/year			5 576 846		1 443 335
		Cost increase		**Cost increase**	
Costs - shortfalls, Mscm/year	0	-172	-27 584 000	0	0
Net value (benefits - costs), EUR/year			33 160 846		1 443 335
System specific power consumption, Wh/scm	33.82				
System specific costs, EUR/Mscm	1765				

In general, the action with the highest net value should be recommended, and since the model provides a positive net value compared with both actual operation and maximum inventory utilisation, operating in accordance with the optimisation model for average system capacity utilisation of 80% is recommended.

Case 2 is an analysis based on a high export pipeline capacity utilisation of 94%. The analysis in section 4.3.2 showed that at and above this utilisation, there was no flexibility in export pipeline inventory with regard to unexpected shutdowns or nomination increases by operating in accordance with the optimisation model. Shortfalls must therefore be expected. In accordance with the comparison between model results and actual data, and as illustrated in Fig. 4–2, model results for high system utilisation are relatively equal to actual operation. For this case, therefore, only comparisons between the optimisation model and maximum operation are made. Table 7–5 shows the base data for Case 2, and Table 7–6 presents the main differences in operating data.

Table 7–5: Base flow rate data for Case 2 - 94% system capacity utilisation

Total nomination	Mscm/d	314
Total export from Kollsnes	Mscm/d	143
Total export from Kårstø	Mscm/d	90
Total production from other fields	Mscm/d	81

Table 7–6: Pipeline operating data for two alternative actions in Case 2

		Optimisation model	Maximum utilisation
Pressure, Zeepipe IIA	bar	195	200
Pressure, Zeepipe IIB	bar	197	200
Pressure, Statpipe I	bar	156	159
Pressure, EuropipeII	bar	185	187
Flow rate, Zeepipe IIA	Mscm/d	72	72
Flow rate, Zeepipe IIB	Mscm/d	71	71

Table 7–7 shows the differences in benefits and costs for Case 2. As in Case 1, maximum pipeline inventories imply higher pressure values and therefore higher system operating costs than operating in accordance with the established recommended inventory levels.

It is assumed that no shortfalls will arise with maximum operation because operating flexibility is high enough to avoid them. However, shortfalls may be expected in model operation. The value presented in the table is calculated in accordance with the analysis in respect of the consequences for delivery security, presented in Paper VI. The analysis showed that pipeline utilisation was higher than 94% on 50 days per year. Furthermore, nomination increases had occurred on 13 of these days, and the maximum rise was 3.7% of maximum capacity. Based on these data, shortfalls owing to nomination increases are likely to be about 160 Mscm/year (13 d/year*0.37*334 Mscm/d). The analysis of historical shutdowns showed that there were about 0.2 shutdowns on average per day for a pipeline. A typical shutdown lasted for three hours and had a size of approximately 10% of pipeline capacity. Based on these data (and the fact that pipeline utilisation of 94% occurred on 50 days per year), expected shortfalls owing to shutdowns can be calculated as approximately 40 Mscm/year (50 d/year*0.2*0.10*334 Mscm/d*(3 hr/24 hr)). Together, this adds up to expected shortfalls of 200 Mscm/year. The value of these shortfalls is much higher than the benefits from reducing power consumption and environmental emissions. The net value of operating in accordance with the optimisation model compared with maximum operation is therefore negative for this case and should not be recommended.

Table 7–7: Costs and benefits for Case 2 with optimised system operation

	Model results	**Model results versus maximum utilisation**	
		Cost reduction (benefit)	
		Quantity	**Value, EUR/year**
Power consumption of electric motors, Kollsnes, kW	188 608	2 023	1 063 289
Power consumption of electric motors, Kårstø, kW	53 024	919	483 026
Power consumption of gas turbines, Kårstø, kW	105 881	106 530	0
CO_2 emissions, Kårstø, Mscm/year	268	1	130 000
NO_X emissions, Kårstø, tonnes/year	2 053	2	4 000
Sum benefits			1 680 315
		Cost increase	
Costs - shortfalls, Mscm/year	200	200	32 000 000
Net value (benefits - costs)			-30 319 685
System specific power consumption, Wh/scm	35.80		
System specific costs, EUR/Mscm	1857		

7.3.5 Sensitivity analysis

Operation of gas export systems is dependent on several properties, which may have uncertain assigned values and may also vary with time. Variations in the following operational variables and their effects on operating costs or net value have been investigated:

- pipeline pressure (and thereby compressor discharge pressure) and inventory
- total system flow (customer nominations).

Variations in pressures and inventory

Figure 7–2 presents the increases in pipeline discharge and inlet pressure (which also represent the compressor discharge pressure) and in operating costs from increasing the inventory in one export pipeline. Inventory is increased from the minimum, which implies a minimum pipeline discharge pressure, up to plausible upper bounds of pipeline pressure and inventory values for average pipeline flow rate. The analysis has also been performed for other flow rates, with similar results. The red dot in the figure represents the recommended pressure values relative to the minimum values. An inventory increase of 10 Mscm for the pipeline represents a rise of approximately 10% in discharge pressure and an increase in operating costs of about EUR 4 000/d.

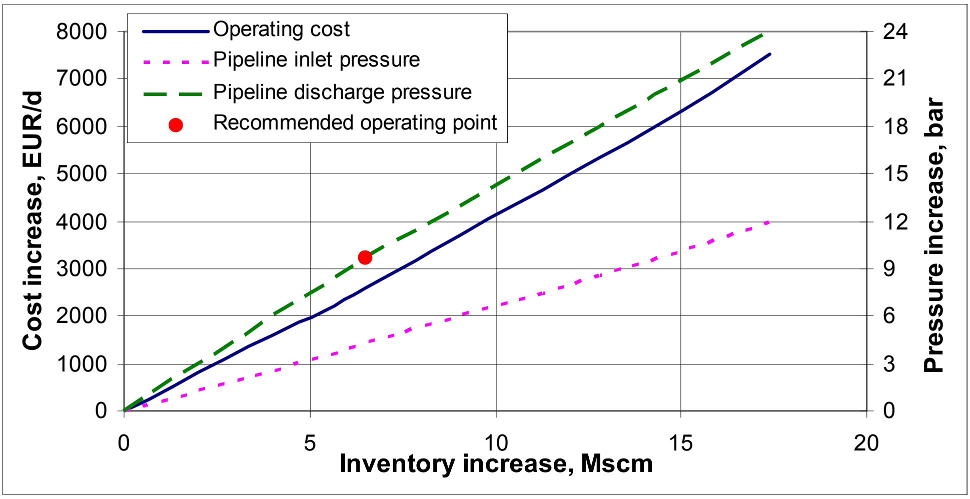


Figure 7–2: Variations in pipeline inventory and pressures and impacts on costs

Changing the pipeline inventory will affect delivery security. Figure 7–3 shows how a change in pipeline inventory influences the size of a possible nomination increase within a lead time of two hours. A 10-Mscm inventory increase implies a possible nomination increase of seven-eight Mscm/d, which equals 17% relative to the initial flow rate. Changing the recommended export pipeline inventory and pressure levels in the optimisation model will therefore increase costs from operating in accordance with this model, and thereby reduce the net benefit of the base case - Case 1. Shortfall costs will not change, since they are assumed to be zero in the base case, and the net value will be reduced.

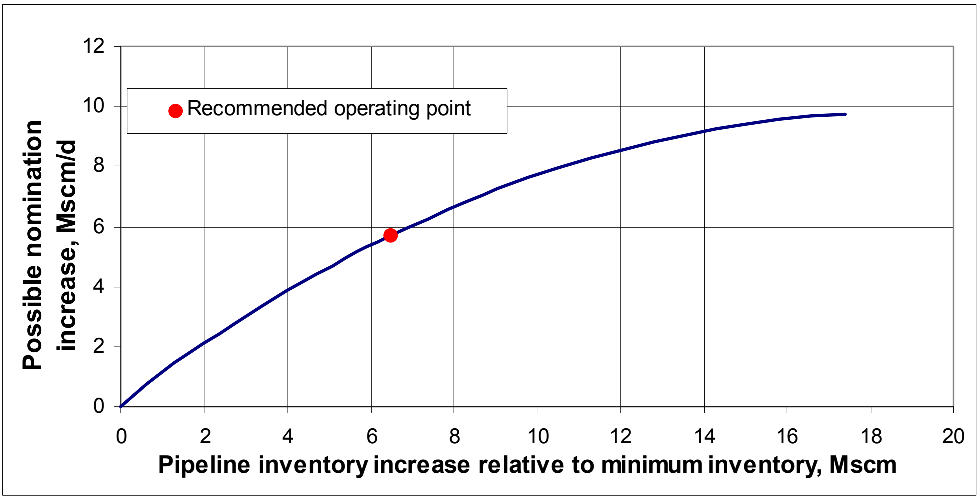


Figure 7–3: Variations in pipeline inventory and impacts on possible nomination increases

Variations in total system flow

Cases 1 and 2 in the previous section demonstrate the impacts on net value from changing total system flow from average to high utilisation. In this section, the net benefit from low system utilisation - represented by utilising 60% of system capacity - is analysed. For the current operation action, trends in actual inventory levels are compared with recommended levels, as shown in Fig. 4–2, and typical export pipeline pressure values corresponding to these trends are found. The system operation model is then run for these pressure values. The results of this analysis are shown in Table 7–8.

Table 7–8: Benefits for 60% capacity utilisation from optimised system operation

		Model results versus			
		typical operation		**maximum operation**	
	Model	**Cost reduction (benefit)**		**Cost reduction (benefit)**	
	results	**Quantity**	**Value, EUR/year**	**Quantity**	**Value, EUR/year**
Power consumption of electric motors, Kollsnes, kW	72 150	3 790	1 992 024	15 720	8 262 432
Power consumption of electric motors, Kårstø, kW	28 110	1 690	888 264	8 560	4 499 136
Power consumption of gas turbines, Kårstø, kW	40 900	200	0	6 520	0
CO_2 emissions, Kårstø, Mscm/year	104	0.4	43 000	24.4	2 442 000
NO_X emissions, Kårstø, tonnes/year	705	7	13 400	391	781 200
Sum benefits, EUR/year			2 936 688		15 984 768
System specific power consumption, Wh/scm	25.86	1.04		5.64	

Together with Cases 1 and 2, this analysis shows that net benefits from operating in accordance with the optimisation model (with the recommended inventory curves) are increased by reducing system capacity utilisation below the average utilisation level compared with maximum operation. Above average utilisation, the net value remains approximately constant. The net benefits for model results compared with actual operation also increases with reduced system utilisation. For Case 1 (80% capacity utilisation), however, the net benefits for model results compared with actual operation is higher than in the case of 60% utilisation. This is because in Case 1, the model results are compared to actual operating data for a specific day. In the case presented in this section, the established operation model is run for typical data based on trends in actual data. Hence, in general, net benefits will increase with a decrease in system capacity utilisation. The three cases also shows that the impacts on net benefits for maximum operation are higher than for actual operation - i.e, net value is more sensitive to flow variations in the maximum operation scenario.

Maximum operation clearly has the highest net value for high system utilisation. With system utilisation lower than 80%, it can be assumed that no shortfalls will occur with any of the three actions and that net value equals net benefits. With such utilisation, operating in accordance with the optimisation model has the highest net benefits.

Figure 7–4 shows the impacts on net benefits and net value for the three different levels of system utilisation. Differences in expected shortfall costs between model results and actual operation are difficult to predict and the net value of this action is therefore not presented.

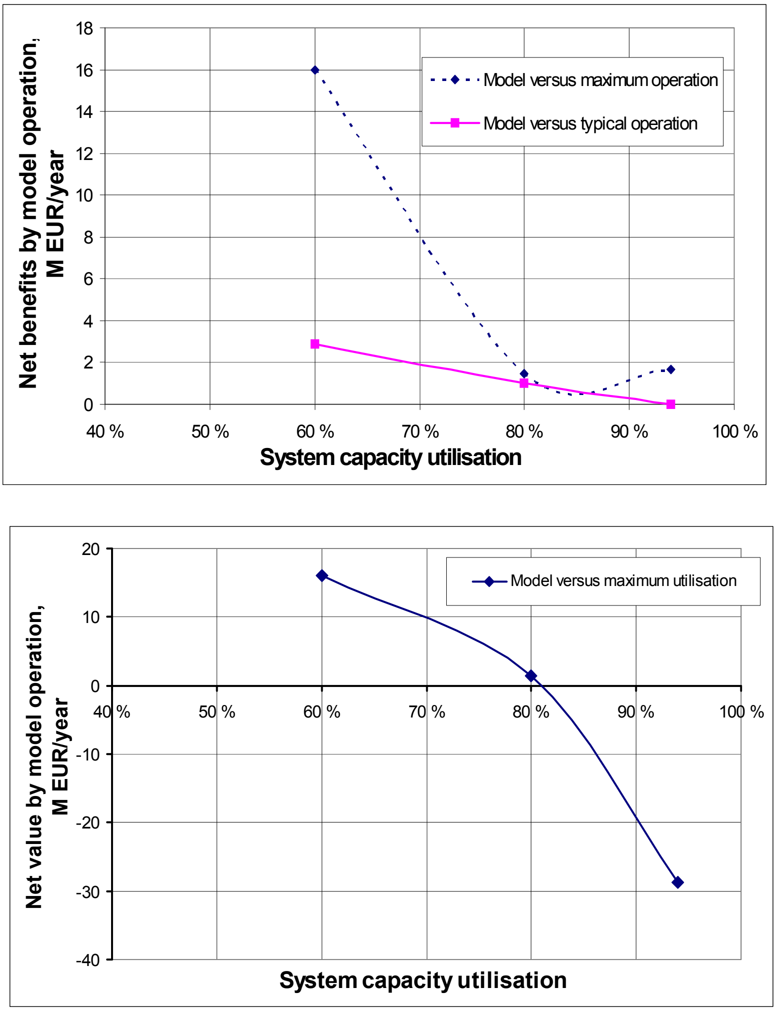


Figure 7–4: Impacts on net benefits (a) and net value (b) by varying system utilisation

The following variations in system parameters have been investigated:

- short term gas price
- electricity price
- taxes on CO_2 emissions
- taxes on NO_X emissions
- inlet temperature of compressors
- inlet pressure of compressors
- gas molecular weight
- pipeline ambient (sea) temperature.

Variations in those parameters likely to have the largest impacts on system operation configuration and the highest uncertainty are presented. These are the first four in the list above - the values for energy and emissions. The four subsequent parameters related to ambient conditions and gas molecular weight will be more thoroughly investigated in later work. However, preliminary analyses show that the influence of variations in these parameters on optimum operation of the system is limited, and in the same order of size as the effect of a degraded compressor presented in section 5.4.

Variations of energy prices and emission taxes

In the analysis presented above it is assumed that CO_2 and NO_X taxes bear all the costs associated with the respective emissions. As stated in several studies (presented in Paper VI and chapter 2), however, a large proportion of costs relate to these emissions, so that their value should be set much higher than today's taxes. Paper VI has presented and discussed the effects of varying prices for electricity and emissions in the model. These prices are varied in accordance with the reviewed studies on emission and energy pricing. Table 5 in Paper VI presents the effects of these variations for the Kårstø compressor station. According to the table, varying electricity and emission prices influences both flow distribution through compressors and total system operating costs. Reducing electricity prices increases the flow rate in the electrically-driven KEP compressor up to its maximum capacity. Reducing emission prices reduces the flow rate in the KEP compressor and increases the flow rate in the Statpipe compressors. Figure 7–5 illustrates the sensitivity of varying energy and emission prices. The figure shows that system specific operating costs are more sensitive to price variations for electricity and CO_2 than for NO_X. The sensitivity of operating costs to electricity and CO_2 is approximately equal. However, since the probable price variation range is larger for CO_2, the variation in this value has the largest effect.

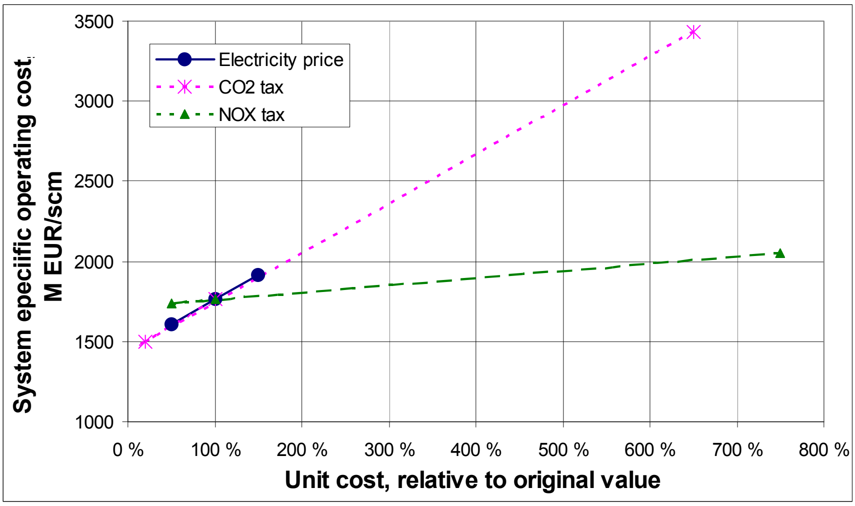


Figure 7–5: Sensitivity of varying prices for electricity and emissions in the model

Differences in system operation owing to variations in electricity and/or emission prices result in changes to the net benefit from operating in accordance with the model.

Figure 7–6 shows the effect on net benefits for Case 1 (see Table 7–4) by varying these prices as presented above. Compared with actual operation for this case, increasing electricity prices leads to a higher net benefit, while increasing the emission prices results in a decrease in the net benefit from operating in accordance with the optimisation model.

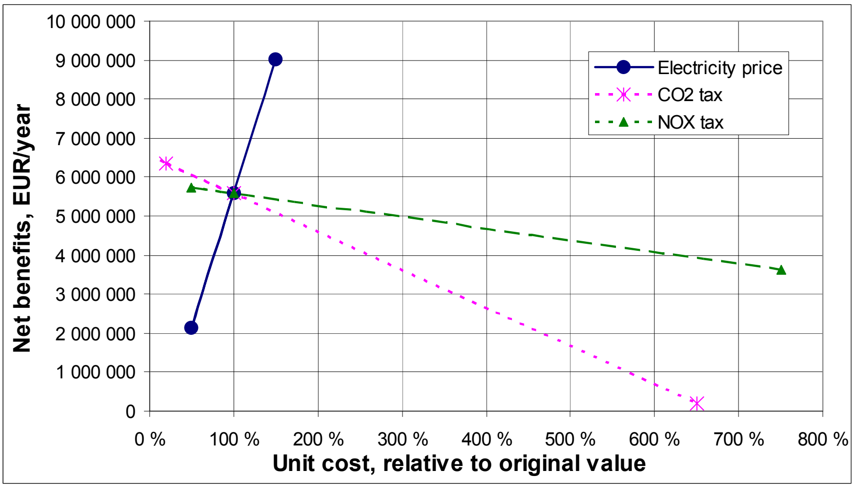


Figure 7–6: Effects on net benefits for Case 1 from varying prices for electricity and emissions

Variations in short term gas price

According to IEA statistics [36], natural gas import prices in Europe varied between about EUR 0.10-0.25/scm of gas during the 2005-2007 period. Figure 7–7 shows the effects on shortfall costs of varying the gas price by 50-200% of the base price (EUR 0.16/scm) through an annual shortfall of 172 Mscm (Case 1).

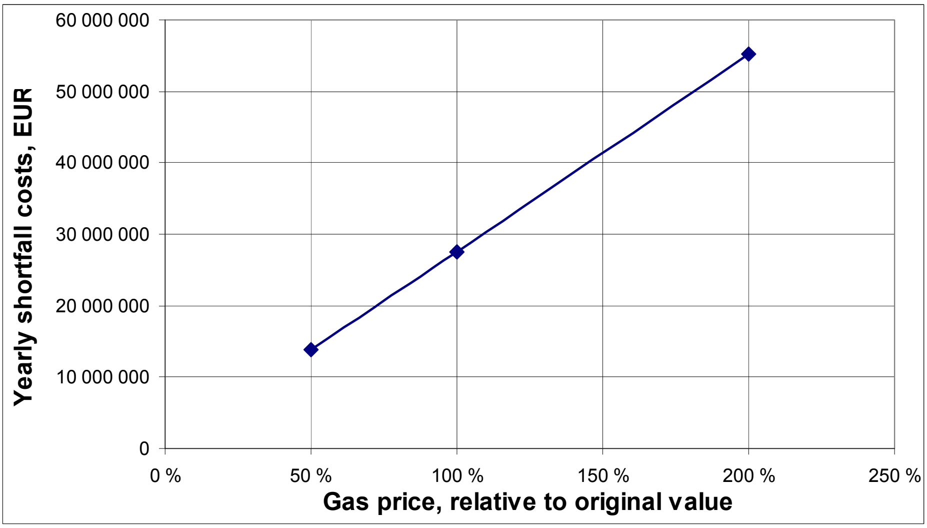


Figure 7–7: Effects of variations in the gas price

7.4 Discussion

7.4.1 Recommendations from the CBA

Table 7–4 showed that, for average system capacity utilisation, operating in accordance with the established optimisation model comprising the recommended inventory curves yields a positive net value both compared with both actual and maximum operation and should be recommended. At this level of capacity utilisation, model compared with actual operation typically implies a different flow distribution in the system, lower pressure drops across system elements and lower pipeline inventories, as discussed in chapter 6. Figure 4–2 also illustrates that, at 80% system utilisation, operating in accordance with recommended inventory levels typically implies a lower export pipeline inventory level than with actual operation. Lower pipeline inventory is also the reason for a positive net value compared with maximum operation.

Shortfall costs in the analysis are calculated as gas sale losses and based on the short term gas price. Possible damage to company reputation and costs for society if customers do not receive their nominated gas quantity have not been calculated. These costs are hard to quantify. Since they represent customer aspects, it can furthermore be assumed that they will only appear if shippers cannot cover the deficit gas (shortfalls) in the short term market. So costs will relate either to lost gas sales or reputational damage and missing gas for customers. The latter costs are assumed to have the same value as the costs of gas sale losses. For the society as a whole, therefore, no differences will exist between these two events.

The difference in shortfalls between model and actual operation may have been placed too high, so net value should be lower. In any event, operating in accordance with the model yields a net benefit, and should therefore also be recommended, even if shortfall costs are not taken into account. The reason for shortfalls in actual operation may be that the system operator does not know enough about available gas inventory in the system, and of how much change in nominations or decreases in shortfalls can be handled. Shortfalls might have been avoided were this known.

For high system capacity utilisation, operating in accordance with the recommended inventory levels could result in shortfalls, since there will be no operating flexibility for nomination increases or shutdowns. Since the value of sold gas is about 100 times larger than export compressor operating costs, savings from reduced power consumption and lower environmental emissions will not compensate for the lost gas sales. At high capacity utilisation, therefore, operating in accordance with maximum export pipeline inventory levels is recommended where possible. However, it should be noted that this will also restrict operational flexibility, since no further opportunity exists for increasing pipeline inventory. That might be necessary in the event of shutdowns downstream from export pipelines.

In accordance with the analysis presented in section 4.3.2, the range from 85-94% of maximum pipeline capacity is a transition area. This needs further investigation to determine exact operational recommendations. Varying the inventory levels (as presented in the sensitivity analysis, Fig. 7–2) will change the range of the transition area and thereby level of capacity utilisation at which it is profitable to operate in accordance with the established recommended inventory curves and maximum operation respectively. At low system capacity utilisation, operating in accordance with the model represents a high net value compared with both actual and maximum operation, and is recommended.

The analysis presented is based on a two-hour lead time after a re-nomination before the discharge pipeline flow rate increases. This represents an extreme case. Capacity in the pipelines is booked on an annual and monthly basis, and exit terminal nominations are made both weekly and daily. The operator therefore knows roughly how much gas is to be delivered from day to day and can prepare the necessary pipeline inventory in advance. Expected shortfall costs owing to nomination increases may therefore be lower than considered in the analysis.

On the other hand, historical deliverability is calculated on the basis of relationship between the volume of gas delivered to the customer and the latter's latest nomination rate. This does not necessarily represent the exact relationship between the gas volume which the customer originally wanted and the amount it received. This is because nominations may be continuously varied throughout the day by both operator and customer, and the last prevailing nomination value is applied in the calculation. A new term for deliverability should therefore be created to represent this relationship and to analyse nomination fulfilment.

The focus on environmental emissions, pressure to enhance energy efficiency and growth in world energy consumption and demand have all increased over the past few years, and are important issues for the sustainability of the planet. Reductions in emissions and power consumption may therefore be valued much more highly than the cost of lost gas sales. In addition, as discussed in chapter 2, valuing environment and energy is not easy. Also, the current Norwegian NO_X tax is expected to increase in near future. The discussion illustrates that the environmental costs could be assigned a higher value than the base values in this CBA. That would result in recommendations to operate at relatively low pipeline inventories and pressures.

The sensitivity analysis presented in this chapter shows that system operation and net value are highly sensitive to variations in total nominations, size of pipeline inventories and variations in energy and emission prices. The effects have been analysed by varying one variable or parameter at a time. However, more of the parameters and variables will have interdependencies. Examples of such interdependencies are the relationship between energy prices (gas and electricity) and emission taxes, and between total customer nominations (demand) and the price of gas. These interdependencies are not analysed in this work because it would make the analysis too complex. They should be more thoroughly investigated in later work. However, a partial sensitivity analysis has given a good representation of which parameters and variables have large effects on the end result.

Based on the model validation and the positive net value in the CBA, implementation of the optimisation model in actual operation is recommended. Implementation is presented in the next chapter.

7.5 Conclusion

This chapter supports objective E by performing a CBA of the optimum operation of a gas export system. Part of the analysis is also presented and described in Papers III and V.

The analysis shows that the net value from modifying system operation in accordance with the established optimisation model, compared with current operation, is positive for all levels of system capacity utilisation. Benefits related to reduced power consumption and emissions are higher than the potential gas sale losses caused by insufficient pipeline inventory levels. The net value is also positive for system capacity utilisation below 85% compared with operating in accordance with maximum export pipeline inventories. The latter implies maximum export pipeline inventory for given flow rates. The reason is that, even though increased gas sales have a considerable higher value than the costs of packing this additional gas volume, increased gas sale incomes imply that the additional packed gas is sold. Analyses have shown that the recommended system inventory will cope with most increases in demand for this level of system utilisation. Packing more gas will therefore only imply costs with no additional revenue. If flow rates are at or above 94% of system capacity utilisation, operating in accordance with the system operation model but using maximum export pipeline inventory instead of the established recommended inventories is recommended to avoid large shortfalls.

However, the size of the net value for each action and level of capacity utilisation is heavily dependent on the value of key parameters and variables. The value of several of these is uncertain. This must be carefully considered when deciding on system operation and implementing the model.

8 Guidelines and implementation in system operation

8.1 Introduction

The focus in this chapter is on developing visual and descriptive guidelines for optimum operation of the gas export system based on the established models. These guidelines are established for implementation in strategic planning and operation at system operators, and follow the validation, sensitivity and cost-benefit analysis of the model. The guidelines have been established in co-operation with the system operator.

8.2 Implementation of the models

The established mathematical models should be implemented at the system operator, and integrated with existing software which registers real-time data on customer nominations, production rates, operating conditions and characteristics of system facilities. In this way, the models can be run at any time for the specific system state. The model results will then give recommendations for optimum operation of the system at the given state. Before the recommendations are put in effect, they should be evaluated by the operator to ensure safe and feasible system operation. In a given situation specific constraints might have to be taken into accounted but which are not included in the general model. Results from the models may also be used in existing forecasting models at the operator to determine the actual consequences for system operation and gas blending of using the results.

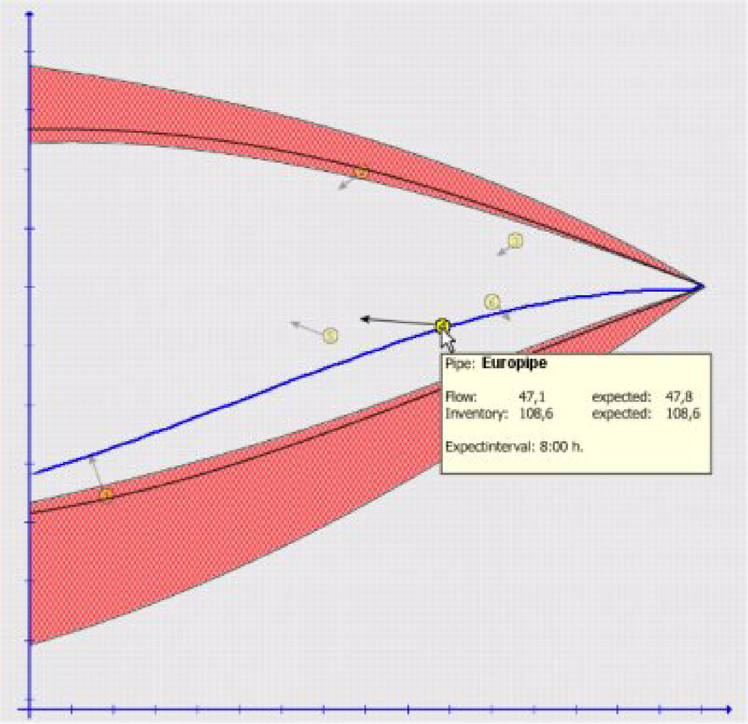
In real-time operation, visual displays and descriptive operational guidelines may be more applicable than running computer models. Visual displays will provide the opportunity for system operators to see where the actual operating points are compared with optimum operation for both pipeline and compressor station operation. Furthermore, descriptive guidelines will provide general recommendations on how to operate the system for the given state. Such visual and descriptive guidelines are developed on the basis of running the optimisation models for different typical cases, and are presented in the following sections.

8.3 Visual guidelines

Visual guidelines have been developed in this work for pipeline operation, compressor station operation and for strategic longer-term planning. The purpose of the pictures is to display real-time operating points compared with optimum operation for a given system state. In addition, the pictures will provide the system operator with better understanding of the operation of specific system elements and their influences on total system operation. Some suggestions for visual guidelines are presented in this section. Further development of such displays is on-going work.

8.3.1 Pipeline operation

Figure 8–1 shows actual pipeline inventory for the export pipelines (yellow circles) compared with recommended (blue curve), minimum and maximum inventory (black curves in the red area) as a function of pipeline flow on a normalised basis. It also displays the direction in which the inventory/flow values move. The operating point for all export pipelines is presented in the same display. Because of some physical differences between the export pipelines, the minimum and maximum curve will differ and is therefore represented as a shaded area. By pointing on one specific pipeline operating value, however, it is possible to see the minimum, maximum and recommended inventory curves for that specific pipeline, as illustrated in the figure. The figure will provide information about whether to adjust pipeline inventory, and should be related to the cost of changing inventory (Fig. 7–2) and to future pipeline nomination plans.



Pipe: **Europipe**

Flow: 47,1 expected: 47,8
Inventory: 108,6 expected: 108,6

Expectinterval: 8:00 h.

Figure 8–1: Export pipeline inventory and flow rate

Shippers might want to change their nominations within a day. Figure 8–2 shows how much the gas flow in the export pipelines can be increased within a nomination lead time of two hours for a given flow rate. The shaded area represents the recommended area for all pipelines, and is based on the optimum inventory. The yellow circles represent actual operating points, provided by online data. Pointing at one of the actual operating points will call up the actual and recommended curves for this specific pipeline. In the particular case illustrated in the figure, the actual points pointed at represent operating at a higher inventory level than the one recommended. Based on the information from this figure, the operator can accept or reject a shipper's request for re-nomination.

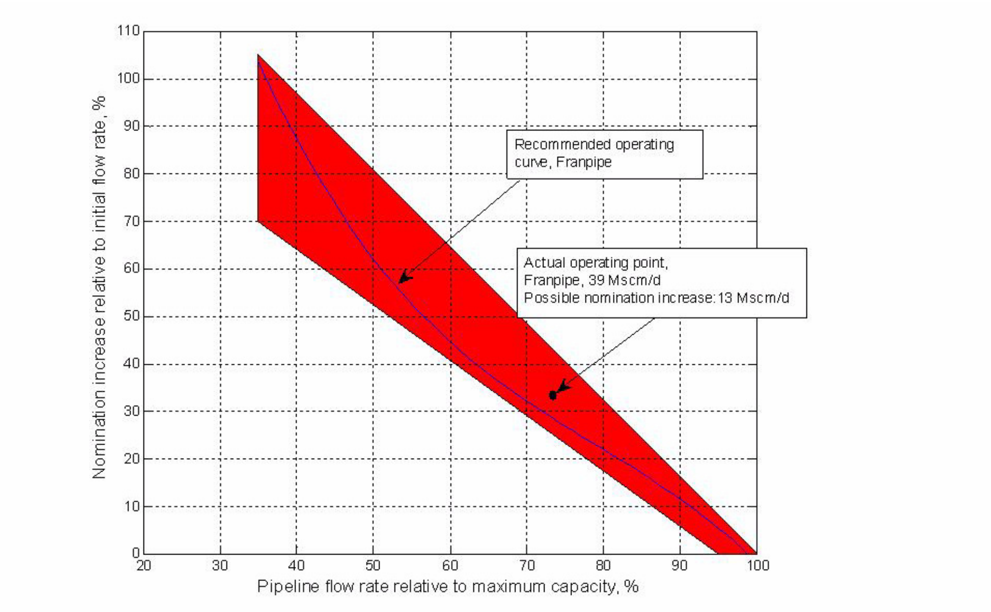


Figure 8–2: Possible relative increase in nomination

The export pipeline can store a large amount of gas, and it may be of interest for system operators to start selling pipeline storage capacity to shippers. In this case, it is important to know the cost of increased pipeline inventory and thereby pipeline pressures. Figure 8–3 shows the daily operating costs of export pipeline inventory changes for all export pipelines as a shaded area, together with the actual pipeline operating points (corresponding to Fig. 7–2).

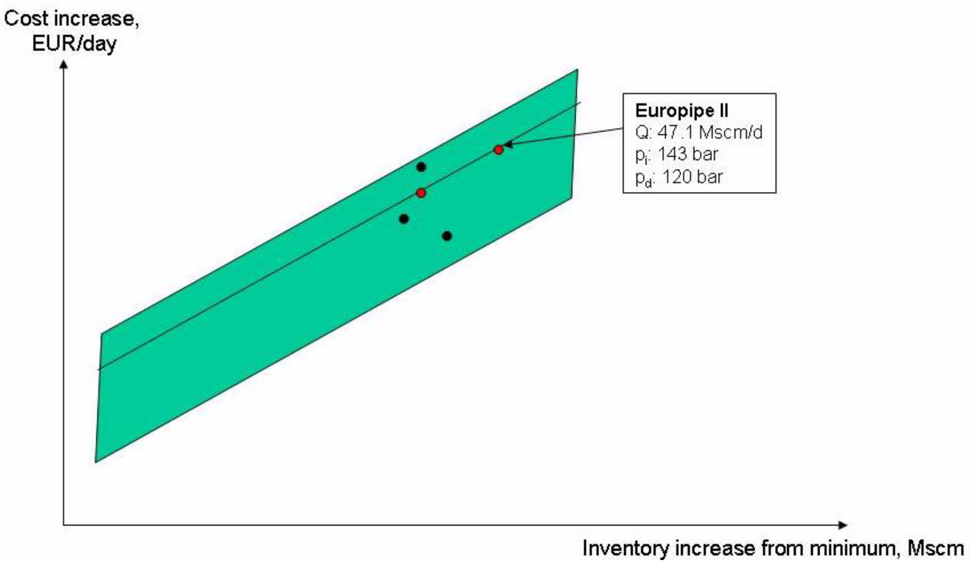


Figure 8–3: Costs of changing export pipeline inventory

When one of the pipeline operating point is selected, it turns red, The recommended point for the pipeline at the given flow rate will also appear (as a red point), together with the specific pipeline curve showing the cost of adjusting the inventory. The figure will be connected to online data, so that they will be adjusted instantly in accordance with flow rate changes.

8.3.2 Compressors operation

The most efficient number of compressors for use with certain pipelines connected to the compressor station is a function of both flow and inlet pressure of the connected pipelines, in addition to compressor operating conditions (such as inlet temperature, pressure and molecular weight). Figure 8–4 gives recommendations on how many compressors should be in operation for a given flow and pressure in each of the intermediate pipelines connected to the Kollsnes export compressor station - Zeepipe IIA and IIB - in this case. The shaded area represent values for different flow rates and pressures. The black circles represent actual operating points. Pointing at one of these will call upon black curves in the figure showing specific power consumption for different number of compressors in operation for that specific pipeline. The display must be integrated with online data for parameters such as inlet temperature, pressure and molecular weight. The areas and curves in the graphic will move when some of these parameters change. One should seek to operate with the number of compressors which corresponds to the lowest specific power consumption. As illustrated below, this will be three rather than two for IIB. At this specific flow rate, the curve for three compressors is below that for two. However, the figure also shows whether the difference between one more or one less compressor exercises a considerable influence on compressor station efficiency. The figure must therefore be seen in connection with compressor start-up costs as displayed in Fig. 8–5.

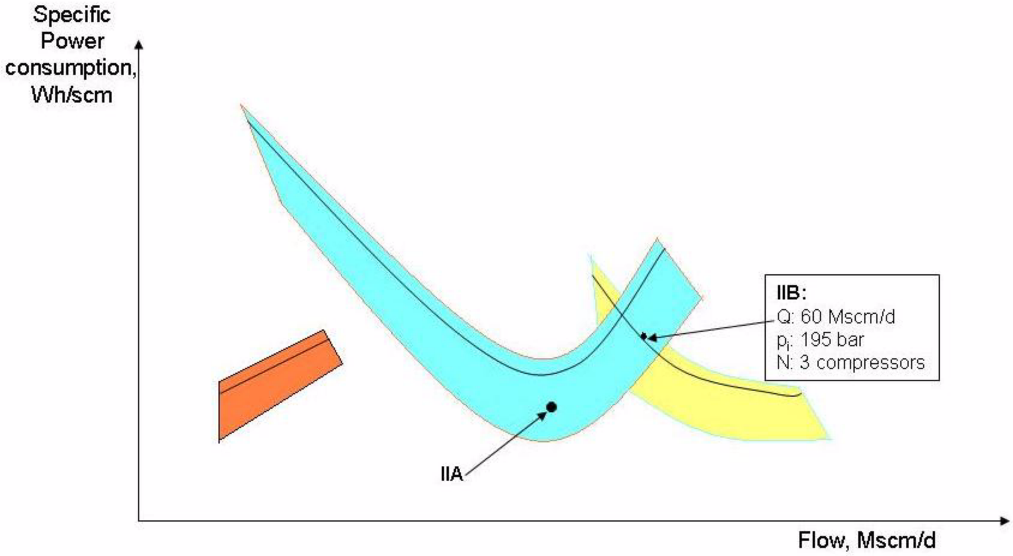


Figure 8–4: Number of compressor in operation connected to intermediate pipelines

If optimum compressor station operation requires the start up of compressors, costs related to this operation should be evaluated before initiating the operation. Figure 8–5 shows compressor start up costs as a function of required compressor flow and pressure. Pointing at the operating point for one specific pipeline will call up the start up costs for achieving the required flow and pressure for a compressor connected towards this pipeline.

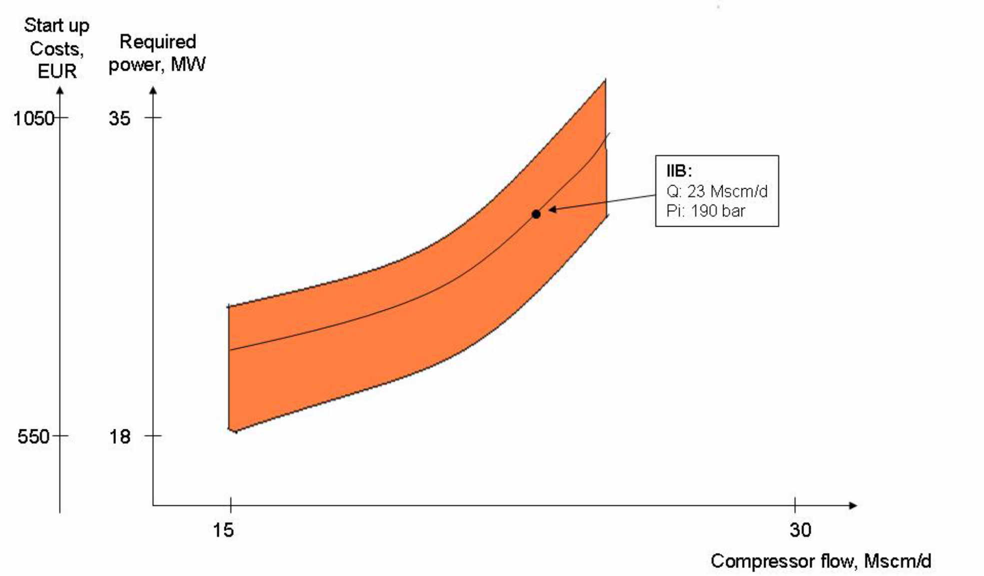


Figure 8–5: Start-up costs of a compressor

Visual displays of compressor operation should exist both at the system operator and at the operator of specific compressor stations to provide better understanding and co-operation between the different operators.

8.4 Descriptive guidelines

In addition to the visual guidelines, the following recommendation for descriptive guidelines have been established for system operation:

- The operator should endeavour to allocate compressors and flow equally between Zeepipe IIA and IIB at the Kollsnes processing terminal.
- The crossover at Kollsnes should only be used if one of the compressors is inoperative.
- Starting up an extra compressor compared with using the crossover leg will be the most efficient operating alternative if the extra compressor is needed for a minimum of 15 hours.
- For all situations (all pressure levels) in which the total flow rate from Kollsnes is above 120 Mscm/d, the most beneficial solution is to have six compressors in operation.
- Pressure drop over node platforms (such as Sleipner and Draupner) should be below five bar. If this is not the case, the pressure in pipelines upstream from the platforms should be reduced.

- The electrically-driven KEP compressor at the Kårstø compressor station should be operated at full load. (As long as this does not conflict with related pipeline nominations)

8.5 Discussion

The guidelines and displays presented in this chapter are specific for specific system facilities and in part for system conditions. They are developed to provide a representative presentation of how these will look in actual operation. However, they can be extended to other, similar facilities and operating conditions.

Furthermore, graphics have been developed for the number of compressors in use with a specific pipeline. Compressor stations are often connected to several pipelines, and choosing the number of operating compressors also depend on such conditions as the pressure difference and flow distribution between the pipelines. However, flow distribution between the pipelines can be varied to a certain extent.

Visual and descriptive guidelines as presented in this chapter have been presented to and discussed with the system operator Gassco. The Guidelines will be implemented in the operation of the Norwegian gas export system, and this work is on-going.

Implementation of the established optimisation model in operations depends on integration with existing models for measuring and logging online operating data, and on plans for future nomination and production rates. Integrating the model with such software can make running the model useful in planning system operation. The operational flexibility of the established optimisation model is high. Specific system or operating restrictions which might restrict this flexibility include:

- requirements for mixing pipeline gas flow to achieve the required gas quality
- rate of oil production, which also governs gas output
- essential maintenance of some system equipment
- defective equipment, which could result, for instance, in decreased pressure tolerances or reduced capacity.

8.6 Conclusion

As a consequence of the positive net value from the CBA and the validation analysis, implementation of operational guidelines is recommended and will be an appropriate tool in actual system operation to:

- increase system energy efficiency and reduce environmental emissions
- enhance understanding between different system operators
- continuously analyse the consequences for gas delivery security of given pipeline inventory levels
- understand the consequences for compressor station efficiency of varying pipeline flow and/or starting up a compressor
- identify the costs of certain operational choices such, as extra packing of gas in the pipelines and starting up an additional compressor.

9 Main results

This chapter will present the main results from the work performed. These results are based on the work presented in the papers and in the previous chapters. The main conclusion and contributions of the work build on these results.

Analyses have shown that pipeline inventory has historically been too high (Chapter 4 and Paper I). At an average pipeline utilisation of approximately 70-80%, pipeline inventory in actual operation is about 5% higher than the recommended level (Fig. 4–2). At lower levels of utilisation, the difference is even higher. For a typical pipeline, a 5% inventory reduction corresponds to approximately 5 Mscm of inventory, and this corresponds to a reduction of about 3 bar in pipeline inlet pressure and corresponding compressor station discharge pressure (Fig. 7–2). At high utilisation, actual pipeline inventory level equals the recommendations.

Furthermore, the work has developed mathematical operational models of the Kollsnes and Kårstø compressor stations. The established models describe the performance of the Kollsnes and Kårstø compressor stations to a sufficient level. (Chapter 5 and Paper III.) The result yielded by the Kollsnes compressor station model from a reduction of 3 bar in compressor discharge pressure for average system utilisation is a cut in specific power consumption of approximately 0.7 Wh/scm (Chapter 5 and Paper II). For a typical day, this equals about 3.5 MW - corresponding to EUR 5 000/d for the electrically-driven compressors.

Operating the Kårstø compressor station in accordance with the recommended pressure levels will reduce specific power consumption for the gas turbines at this facility by approximately 0.05 Wh/scm. For typical gas flow rates through the gas turbine-driven compressors, this corresponds to a power reduction of 100 kW. This also corresponds to a reduction of about 0.2 Mscm per year in CO_2 emissions (in accordance with Fig. 5–8) and a reduction of about 2.5 tonnes per year in NO_X emissions. (Chapter 5.)

Furthermore, the work has developed a system optimisation model based on the recommended pipeline inventory curves, the compressor station models and the results from analyses of system integration, constraints and requirements. This model has been validated against the real system performance and found to describe it sufficiently (Paper VI). Operating in accordance with the established system optimisation model provides additional benefits for energy efficiency. The model provides recommendations on how to distribute gas between the compressor stations and the intermediate pipelines in an optimum way, which typically involves a more equal distribution of gas flow between compressors and pipelines. Furthermore, the model often recommends having more compressors in operation (primarily at the Kollsnes compressor station) compared with typical operation. Another important recommendation is operating the electrically-driven KEP unit at Kårstø at full load to minimise system specific power consumption and environmental emissions. (Chapters 5 and 6 and Papers III and VI.)

This work has further developed a consequence analysis of delivery security in the event of nomination increases and unexpected shutdowns. At and below average system utilisation of 70-80%, this analysis confirms that operating in accordance with the recommendations provides sufficiently high levels of pipeline inventory (Chapter 4 and Paper VI). However, at high utilisation, defined as flow rates above about 94% of pipeline capacity utilisation, no flexibility exists at the recommended levels. Operating in accordance with the recommended inventory levels at this level could therefore result in shortfalls. The recommended curves should therefore be employed mainly when flow rates are below this value. At high capacity utilisation, the work recommends operating at maximum inventory levels for the export pipelines (EPs) where possible. (Chapter 7.)

Based on the results of all the work performed, the author has concluded that a potential exists for reducing system pipeline inventory by approximately 5% at 70-80% capacity utilisation (average utilisation) in several export pipelines. This implies a reduction of about 3 bar in compressor station discharge pressure. Optimising the compressor stations and the system in accordance with these values by using the established optimisation model corresponds to a cut in power consumption and operating costs of some 3.5 MW and EUR 5 000 per day. This adds up to an annual value of almost EUR 2 million. Applying the established model for an average system utilisation mode is therefore favourable in terms of energy consumption and environmental emissions. These recommendations also ensure that nominations are fulfilled.

Descriptive and visual guidelines have been developed for implementing the results obtained in the actual operation of the gas export system (Chapter 8). These show different ways to proceed in order to achieve the potential savings in power consumption, emission reductions and operating costs. The visual guidelines (graphs) apply to both pipelines and compressor stations and will provide on-line information of actual operation, represented by a point in the graphs, and recommended operating points. Furthermore, the graphs display the impact on operating costs and delivery security if operation is changed.

10 Conclusions and recommendations for further work

Optimum operation of gas export systems has been established in this work. This chapter summarises the results achieved and drawn conclusions. The main focus has been on the Norwegian dry gas export system.

Different methods have been applied to solve the main problem:
- collection and statistical analysis of operational data
- regression analysis
- compressor and pipeline simulation
- parameter tuning
- linear and non-linear mathematical programming
- constrained non-linear optimisation.

10.1 Conclusions and summations

The conclusions and summations of the main work support the objective and goals specified in section 1.3 and are sorted in accordance with these.

A. System approach and analysis
- All physical and administrative relations between the gas export system elements and the system's interactions with its context have been analysed.
- The main problem has been decomposed into three sub-problems and related to the different physical system elements.
- Sub-solution approaches have been established and related to each sub-problem (goal), and the approaches aggregated into a solution approach to the main problem.
- Relevant requirements - financial, technical and legal - and control variables related to each system element and according with system objectives have been identified.
- Information models have been developed which describe all these relations, interactions, and causal connections.

This work has contributed to the following aspects:
- Overcoming the complexity of the main problem and the system-of-interest by providing a clear and total overview of the whole gas export system, its integrated operation and its elements.
- Finding the best approach to solving the problem which allows for energy-efficient operation of each system element, and merging these into an optimum solution for the whole system.
- Information models which provide increased knowledge of causal connections in system operation which would in general have been difficult to identify, and show which variables govern the operation of system elements, their impact on system performance and how they can be adjusted. These models thereby provide all alternatives for modifying the system and the operation of system elements in order to ensure a valid and best possible solution.

B. Optimum pipeline inventory

- Historical variations in daily nominations and the size and frequency of shutdowns have been analysed. Expected variations in future pipeline flow owing to typical nomination variations and shutdowns have been found.
- A method has been developed for predicting recommended export pipeline inventory as a function of pipeline flow (customer nomination) which takes into account expected flow variations and shortfall events.
- Impacts on delivery security by operating according to the established inventory recommendations are analysed.

This work shows that operating in accordance with the recommended inventory curves will fulfil varying customer nominations, while reducing operating costs related to pipeline inventory.

C. Optimum operation of compressor stations

- Algorithms have been developed which describe compressor station performance for varying ambient conditions, and the required gas flow related to customer nominations and pressures in connected pipelines. These are based on actual compressor station configurations and performance characteristics of compressors, gas turbines and electric motors.
- Constrained non-linear optimisation models based on the algorithms have been developed which minimise specific power consumption and/or operating costs of each station.

This work shows that:

- one compressor at full load is more energy efficient than two in parallel at part load
- a gas flow equally distributed between the two intermediate pipelines connected to the same compressor station is the most energy efficient solution
- for a compressor station which includes a degraded compressor, energy efficient operation implies decreasing flow rate through this compressor while increasing flow rates in the other compressors
- running an extra compressor is more energy efficient than operating the minimum number of compressors, including the potential for using the crossover leg, as long as this does not imply operating the compressors in recycle mode (at the Kollsnes compressor station)
- starting up an extra compressor rather than using the crossover leg will be the most efficient operating alternative in all cases, and start-up costs will be recovered within a maximum of 15 hours compared with the cost of using the crossover
- at the Kårstø compressor station, the electrically-driven KEP unit is the most energy and environmentally efficient compressor and should be operated at full load if the objective function is to minimise specific power consumption. This also minimises environmental emissions from gas turbines driving other compressors in the station. This implies that the required flow in the connected pipeline is not lower than the full load of the compressors, and that parallel gas turbine-driven compressors do not need to be operated in recycle mode.

D. Optimum gas export system operation

- An optimisation model for energy and environmentally efficient operation of the system has been established by combining the work on analysing system relations and requirements, optimum pipeline inventory and compressor station operation.
- The model has two independent (contradictory) objective functions which can be minimised: system specific power consumption and/or operating costs. The model minimises these functions while fulfilling customer nomination and maintaining operational flexibility.
- A validation of the results by comparing the established model with actual system operation has been performed.

This work shows that:

- operating the system in accordance with the model minimises specific power consumption and/or operating costs, and lowers these compared with actual operation
- the savings in power consumption and/or operating costs derive from lower intermediate pipeline and compressor discharge pressures, a more equal distribution of gas flow between compressors and pipelines, often having more compressors in operation, and permitting flexibility between the Kårstø and Kollsnes compressor stations
- minimising either system specific power consumption or operating costs yields two different results for system operation. Minimising costs implies higher utilisation of gas turbine-driven compressors than of electrically-driven units. This is because operating costs for gas turbines related to consumption of fuel (which is virtually free of charge) and environmental taxes are lower in relative terms than the price of power for electrically-driven compressors
- the model can provide the system operator with information on which processing terminal can process and deliver and extra scm of gas into the system in the most efficient manner
- the model can provide the system operator with decision recommendations on nomination instructions to operators of subsystems, such as compressor stations, because it provides information on the most energy-efficient way to operate such systems in accordance with customer nominations.

E. Sensitivity and cost-benefit analysis of gas export system operation

- A cost-benefit analysis of using the established model has been performed. This weighs the benefits of reduced system power consumption against potential gas sale losses owing to inadequate pipeline inventory levels.
- A sensitivity analysis has been performed to determine how sensitive total costs and benefits are to variations in key parameters and variables.
- Visual and descriptive guidelines for use in actual system operation have been developed on recommended pipeline inventory, configuration of compressor station operation and system flow routing.

This works shows that:

- modifying system operation in accordance with the established model provides a net benefit compared with current operation. The benefits related to reduced power consumption are higher than the potential gas sale losses arising from insufficient pipeline inventory levels. This is because the recommended system inventory will manage most increases in demand, and packing more gas will imply only costs without any additional gas sale revenue.
- at high system capacity utilisation (above 94%), maximum export pipeline inventories should be applied when identifying optimum system operation instead of the recommended inventory curves.
- the end result is highly sensitive to the size of pipeline pressures and inventory, total system utilisation, and the price of energy and emissions.

Because of the positive net value, implementing operational guidelines is desirable and will be an appropriate tool in actual system operation to:

- increase system energy efficiency and reduce environmental emissions
- enhance understanding between different system operators
- analyse continuously the consequences for gas delivery security at given pipeline inventory levels
- understand the consequences for compressor station efficiency of varying pipeline flow (customer nominations) and/or starting up a compressor
- provide information on costs related to certain operational choices, such as extra packing of gas in the pipelines and starting up an additional compressor.

10.2 Main contributions

The work has established a model and guidelines for gas export system operation which increase energy efficiency and reduce environmental emissions while fulfilling customer nominations. These are currently under implementation in actual system strategic planning and operation.

Based on the results and conclusions from all the performed work, the author has concluded that a potential exists for reducing system pipeline inventory by approximately 5% at 70-80% capacity utilisation in export pipelines. This implies a reduction of about three bar in compressor station discharge pressure, which corresponds to a cut in power consumption and operating costs of some 3.5 MW and EUR 5 000 per day. This adds up to an annual value of up to EUR 2 millions. The annual emission reduction by minimising power consumption for this system utilisation will typically be 0.2 Mscm CO_2 and 2.5 tonnes NO_X. This solution is therefore favourable in terms of energy consumption and environmental emissions, while ensuring that nominations are fulfilled.

10.3 Recommendations for further work

This section contains suggestions for further work based on the established models and achieved results.

Implementation

Further work involves implementing models as well as visual and descriptive guidelines in planning and operating the system. That will also provide practical experience which will be analysed and possibly used to adjust the model. Part of the foundation for this has already been established. Information models may be used for communicating achieved results and their application in a clear, easy-to-understand way, so that they can be used in system operation. Implementing guidelines is the province of Gassco as the system operator, and represents an ongoing job.

Integration with online system models

Implementing the model in actual operation requires the established models and visual displays to be integrated with existing online system operation models and to become more automated. That is because real-time data on parameters such as nominations, temperatures, pressures and gas molecular weight are inputs to the model, and model results depend on the values of such parameters. More automated and integrated models will be easier to use, less time-consuming, and easier and more flexible to update.

Continuous evaluation and updating

Continuous evaluation is required of actual pipeline inventory, daily and hourly variations in customer nominations and actual shortfalls, as well as evaluation of compressor performance (compressors might be degraded). This may prompt adjustments to optimum pipeline inventory levels which influence optimum system operation. Evaluation of compressor performance may require performance curves to be updated to represent actual performance.

Analysis of causes of system operation differences

Comparing between model results and historical data has revealed some differences in system operation with regard to pipeline and compressor discharge pressures, gas flow distribution between compressors and pipelines, and the use of the crossover leg. These differences will be more thoroughly investigated to establish their causes. This should lead to modifications of actual operation, changes to the model or both. The work is already under way.

Improvements to measurement data

The work has also revealed that the overall effect of uncertainties may be large inaccuracies in measured operational data at processing terminals (instrumentation/ apparatus and software used for logging data). Improvements in measurements data should be made at the terminals to obtain more accurate values.

In addition, deliverability calculations which measure the volume of gas delivered to the customer in relation to their original nominations should be improved. The original nomination is an uncertain parameter, since nominations may vary throughout the day. The last prevailing nomination is applied in the calculation, but this may not equate with the volume of gas originally requested by the customer.

Impacts of gas composition

The effect of varying molecular weight and gas composition between different system components has not been analysed in detail. This may have some effect on optimum operation, especially for possible pipeline routing options and in combining the compressors. However, variations in export gas composition are in most cases neglected.

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Appendix A Paper I on Optimum pipeline inventory

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Appendix B Paper II on Optimum compressor operation

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Appendix C Paper III on Energy efficient gas export operation

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Appendix D Paper IV on Application of systems engineering

Nørstebø, V.S., 2008,
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Journal of Systems Engineering, Autumn 2008, Published Online on May 27 2008.

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Appendix E Paper V on Sustainable gas export operation

Nørstebø, V.S., 2008,
“Application of systems engineering and information models to optimize sustainable performance of gas export systems”,
Paper No. 131, Proc. INCOSE Symposium 2008, NL-Amsterdam.
Best student paper award.

Application of systems engineering to optimize sustainable performance of gas export systems

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Abstract. This paper presents the use of systems engineering in analysis and optimization of gas export system operation. The Norwegian dry gas export system is selected as the subject for the analysis.

There are two important factors that a gas export system shall satisfy. Firstly, the system shall secure that the customers receive the gas that they have ordered. Secondly, the system shall do this in as energy efficient way as possible, i.e. minimize operating costs and environmental emissions.

For the operator of gas export systems it is of vital importance that equipment and pipelines in the system are optimally integrated. This will secure flexibility, capability, availability and energy efficiency of the system, and enhance understanding between different system operators.

This work demonstrates how systems engineering and information models have been applied as tools for analyzing the integration in gas export systems and existing system operation, and further for developing models that optimize the energy efficiency of system operation. The impacts of gas export system operation on the society are investigated by means of a cost-benefit analysis.

Background

The Norwegian continental shelf (NCS) is an important supplier of dry gas to Europe. Norwegian dry gas export was 86.2 bn scm[1] in 2006. The dry gas export accounts for some 15% of total European gas consumption. This makes Norway the second largest gas exporter to Europe and the third largest on a world basis. The gas is transported in a transport network at the NCS, which consists of 7800 km of pipelines, and is the largest offshore gas transport network in the world, see Figure A-1. (MPE 2007) Many routing possibilities exist in this network.

In addition to pipelines, Norway's gas export system includes offshore platforms and land-based processing terminals, which process and compress natural gas. The use of centrifugal compressors is the most common ways to compress natural gas. These compressors are driven by gas turbines or electrical motors. The total operating cost of gas export systems is highly dependent upon the operating cost of the compressor stations. After processing and compressing, dry gas is exported from terminals and platforms through pipelines to customers in the UK and continental Europe.

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[1] Standard cubic meter, scm, defined as the volume under standard conditions – i.e., a temperature of 15°C and a pressure of 1.01325 bar.

Additionally, the export system includes exit terminals, where gas is delivered for sale. Customers at these terminals have the opportunity to make varying gas delivery nominations. Meeting these sales gas commitments is important. Failure to do so would result in gas sale losses, as well as reducing deliverability[2] and hurting the reputation of the gas shippers[3] .

The focus on energy efficiency and environmental emissions related to gas export is increasing, both nationally and internationally. While energy demand is projected to grow substantially over the coming decades, there has been a large concern about the rapid increases in anthropogenic CO_2 and NO_x emissions from fossil-fuel burning. The increases in the atmospheric CO_2 concentrations are expected to contribute to the problems which cause global warming. The petroleum industry is responsible for 29% of the Norwegian CO_2 emissions (MPE 2006). Fauna along the Norwegian coast are vulnerable to NO_x emissions. The national authority has introduced taxes on CO_2 and NO_x emissions.

The challenge is to operate the gas export system at minimum cost, with minimum environmental emissions, fulfilling variations in contractual nominations and maintaining a sufficient pipeline inventory[4] to provide operational flexibility, capability and availability of the system. This requires striking a delicate balance between high pressure and associated energy consumption for compressors on the one hand, and lower pressure and the risk of losing gas sales on the other. It also calls for detailed knowledge of network integration, operational flexibility, the relationship between customer nominations, pipeline flow and inventory, compressor station operation, and the effects on optimum operation.

Problem statement

The main problem is to establish models which will provide guidelines for both technically and economically optimum operation of the Norwegian dry gas export system (NDGES) that increases system energy efficiency, decreases environmental emissions while fulfilling demand requirements. This main problem has been studied in the author's PhD-study. The results are feasible and appropriate in such a way that they can be implemented in actual gas network strategic planning and operation. Further, the models are built on principles that can be extended to other gas export systems.

The gas export system is a large system with many relationships, interactions and system elements. Furthermore, operation of the system is an expensive and complex task that also requires an integration of several technical disciplines. Systems engineering (SE) is a very appropriate tool for analysing the system of interest and optimizing operation of the system. The focus in SE is on optimization and finding solutions of a whole system, rather than individual system elements. It distinguishes the relationships between the different subsystems, system elements and the system context. It also separates the different sub problems of the overall problem and the relationships among them, and helps to aggregate solutions of sub problems to a solution of the main problem. Due to the complexity of the gas export system relationships and operation, use of the SE discipline may lead to better overview, more rational decisions and higher reliability and applicability of the solution of the main problem.

Operation of gas export systems affects the operator, owner and users of the system, as well

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[2] Deliverability is a measure of nomination fulfilment. It is calculated by dividing actual gas delivered by the nominated volume for the year in question.

[3] A shipper is the owner of gas tendered for shipment in the transport system, which has made a booking of transport capacity and will transport gas in the system.

[4] Pipeline inventory is the total amount of gas in the pipeline.

as the remaining society. There is a desire to make the operation more energy efficient and a need for better understanding of costs and benefits by implementing changes in system operation. The use of a systematic cost-benefit analysis (CBA) is one approach that may assist in characterizing explicitly and quantitatively the environmental and economical impacts of gas export system operation on the whole society. The intention with such an analysis is to clarify and systematize consequences of an action before a decision is performed. The analysis will offer a basis for evaluating profitability of an action and ranking different alternatives. Furthermore, a CBA involves a sensitivity analysis that evaluates how sensitive the end results are to variations in key parameters.

Focus. The purpose of the main problem is to find ways on how to operate the NDGES in an energy and environmentally optimum manner.

This purpose of this work is to present ways SE has been applied to the main problem in order to analyse existing operation and the relationships between the different system elements, and to develop a systematic approach on how to optimize operation of the gas export system. Furthermore, this paper identifies and characterizes costs and benefits in operation of the NDGES and describes how optimization of system operation will benefit the stakeholders.

Outline. The paper presents the following elements:
- main theoretical foundation
- the SE process applied in this work
- system objectives and requirements
- information models of the gas export system
- a partial CBA of NDGES operation
- discussion and conclusion

Theoretical foundation

Systems engineering definitions. The system concepts applied in this work are defined here.

In (Asbjørnsen 1992), a system is defined as a structured assemblage of elements or subsystems, which interact through interfaces. The interaction occurs between system elements and between the system and its environment. The elements and their interactions constitute a total system, which satisfies selected functional, operational and physical requirements, over a defined total system life cycle of the system existence.

(INCOSE 2006) defines a system as a combination of interacting elements organized to achieve one or more stated purposes. Further a system element is defined as a major product, service or facility of the system. An element may be an assemblage of subsystems to a higher level system unit. A subsystem is defined as an integrated set of assemblies, components and parts which performs a cleanly and clearly separated function. System elements and subsystems may be system themselves.

The system whose life cycle is under consideration is defined as the system-of-interest (INCOSE 2006).

System context[5] is defined as the surroundings (natural or man-made) in which the system-of-interest is utilized and supported; or in which the system is being developed, produced or retired (INCOSE 2006). The system boundaries separate the system from its context.

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[5] INCOSE [2006] uses the term system environment. In this work, however, the term system context is applied in order to avoid confusion with the natural environment.

The connection between all these concepts is illustrated in Figure 1.

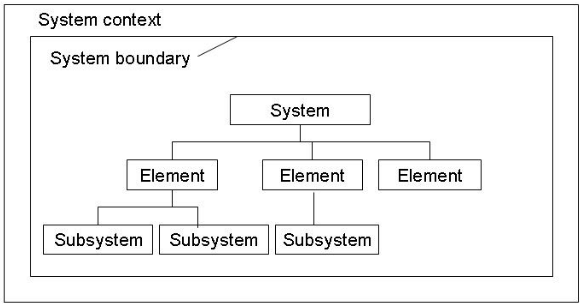

Figure 1. System context and system hierarchy

According to (Asbjørnsen 1992) system integration is the process of identifying and bringing together various technologies, system elements and subsystems, in order to define and deliver a complete system that will fulfil specific design, operational and/or management objectives over system life cycle.

Systems engineering is an interdisciplinary approach and means to enable realization of successful systems (INCOSE 2006). (Asbjørnsen 1992) regards SE as a discipline that involves the analysis, understanding and design of the functional, operational, physical and interface characteristics of large integrated systems with many different elements and sub-systems. It also considers the impact on and interactions with the environment. The SE discipline is an effective way to manage complexity and changes. (Eisner 2002) regards SE as a process of top-down synthesis, development and operation of a real-world system that satisfies, in near optimal manner, the full range of requirements for the system.

According to these definitions, this work focuses on SE as a tool for analysing and understanding interface characteristics of the NDGES, which is a large integrated, real-world system, and its interactions with the context. SE is utilised as a tool for managing the system's complexity, and developing optimum system operation that satisfies the stakeholders' requirements.

Systems engineering in the operation of gas export systems. SE in the operation of the NDGES has also been studied in other works. (Dahl 1999; 2000) presents the use of information models as a tool for assessing Norwegian natural gas transport operations in 1999. His works focus on the evaluation of the changing business environment and new legislative requirements and how they might impact operations. The modelling concentrates on accurately specifying existing behaviour, rather than suggesting optimal behaviour. An identification of stakeholders related to gas transport operations anno 1999 is performed, and this forms a basis for the stakeholder analysis in the work presented here.

(Plummer 1993) describes the structure of the Norwegian offshore oil and gas industry in the year 1993. The work discusses how to select a preferred system configuration in development of new systems.

(Plummer 1993) also points out how SE in oil and gas offshore industries differs from many other SE applications. Oil and gas production and transportation projects are typical one-of-a-kind, unique developments, even if there is some expansion of the systems during their useful life. Their construction makes considerable use of available technology and proven equipment. The focus therefore shifts to ensuring optimum integration of the technology and equipment which are used, and successful operation of the system. In this work, (Plummer 1993)'s view of

SE in gas export operation is applied to the NDGES problem.

Many researchers have studied optimum operation of gas export systems. A review of these works is presented in (Nørstebø et al. 2007b).

This study deals with aspects that are not covered in previous literature. The following factors are combined in a unique manner:

- The work is based on, and analyses the NDGES and operation of this system anno 2007.
- The emphasis is on optimum operation (rather than specifying existing operation), related to the physical components (rather than the business opportunities and the regulatory regime).
- Special focus is placed on the performance and operation of actual system compressor stations, the prime movers of gas in the network.
- The work focuses on operational modifications of an existing gas export system (rather than development of new systems or system elements).
- The model is based on an actual gas export system and its properties, relationships and operational procedures
- A combination of statistical analysis, parameter tuning, simulation and optimization is applied model development.
- The model takes into account that future customer nominations are not fixed, but can be varied throughout the day, by ensuring a certain pipeline inventory.

Cost-benefit analysis. This study utilizes the concepts, practices and principles of CBA as presented in (Boardman et al. 2006) and in (MF 2005).

CBA is a useful tool for decision-making purposes. The intention of the analysis is to clarify and systematise the consequences of an action before a decision is taken. It considers all the costs and benefits (both economical and environmental) to society as a whole[6], and not just a single firm. The analysis offers a basis for evaluating the profitability of an action and for ranking different options. Profitability is evaluated by calculating the net present value (NPV). The major steps in a CBA can be summarized as follows:

- describe the problem and the current situation, and desired/wanted result by initiating actions
- specify different actions and how they will be accomplished
- specify the effects of the different actions
- evaluate and follow-up implemented action

When specifying the effects of different actions, the following tasks should be included:

- decide the impacts - benefits and costs - of the actions
- quantify/monetize all impacts and discount to obtain present values
- compute the NPV of each alternative
- analyse the total uncertainty and perform a sensitivity analysis
- make a recommendation

All potential actions and impacts shall be included, also those with seemingly low probabilities of occurring or low impacts on industry.

If only a single action is evaluated, it should be adopted if its NPV is positive. When more than one option is available, the one with the highest NPV should be selected.

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[6] In SE terms, the society as a whole will be equal to the union of the system and its context.

The systems engineering process

Several researchers have described the SE process and the tasks it comprises, often in slightly different ways. In this work, the process is described as a logical, systematic process that comprises the following tasks, in accordance with (Asbjørnsen 1992):

- Formulate the problem statement. The statement should answer two questions: Why is the problem important? Why is there a need for solution?
- Identify and formulate system objectives. While defining the objectives, the interactions with system context must be kept in mind. The statements which will be formulated should aim to answer the question: What is needed?
- Translate the objectives into functional, operational, physical performance requirements to each system element or subsystem.
- Search for solutions - appropriate technologies and concepts, or methods and algorithms, to satisfy objectives and performance requirements.
- Select and discriminate between the alternatives by trade-off analysis and optimization. This is an iterative process, which shall be performed until the solution is accepted.
- Select the baseline conceptual technology or method.
- Solve the problem.
- Validate that the system satisfy the required performance.

It is important to note that the process is not sequential, notwithstanding most graphical representations. The SE process has an iterative nature and the functions are performed in a parallel and iterative manner that supports learning and continuous improvement. The process is illustrated in Figure 2.

The SE process has been used to analyse the main problem for subsequent optimization. Information models will be developed to accomplish the tasks stipulated in the SE process.

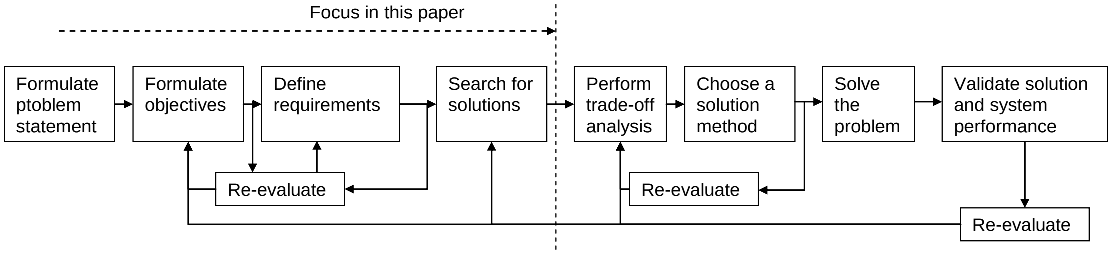

Figure 2. The iterative systems engineering process

This paper concentrates on describing a high-level overview, and not details around each task in the process. It focuses on the first four steps in the process, as indicated in Figure 2. A high-level solution concept is presented. The trade-off analysis and details of the chosen solution methods are presented in other papers (Nørstebø et al. 2006; 2007a; 2007b). The tasks in the SE process related to solving the problem and validating the solution will be performed in later work. However, some aspects and considerations about the last tasks are presented in this paper.

The validation task implies analysing whether the chosen solution method provides a higher total profitability (as regards the society as a whole) than current system operation. This will be done by means of a CBA – an identification of costs and benefits by operating the system.

Stakeholder analysis. Prior to formulation of the problem statement, (INCOSE 2006) suggests conducting a stakeholder analysis. A stakeholder is a party having a right, share or claim in a system. The stakeholder requirements govern the system's development, and they are essential actors in further defining or clarifying the scope of a project. (INCOSE 2006)

(Dahl 1999) identifies the stakeholders involved in Norwegian gas export operation anno 1999. In 2001, a reorganization of the Norwegian gas export operation took place. Since then, some new stakeholders have appeared some others no longer exist. The present stakeholders are as follows[7] :

1. the NDGES operator and owner
2. the Norwegian authorities
3. the European parliament
4. production facilities operators and owners
5. upstream (rich gas and oil) export system operators and owners
6. technical service providers[8]
7. shippers
8. gas customers
9. society

System objectives

The formulation of objectives shall describe what the system actually needs to comply with, and follows the problem statement as presented previously:

"Establish models that will provide strategic and operational guidelines for how to operate the NDGES in an energy and environmentally optimum manner, while fulfilling customer nominations."

(Oliver 1997)'s definition of the term optimum is applied in this work and defined as follows: The best or most favourable degree, quantity or number.

The following main system objectives and the corresponding stakeholders are identified for the problem in this work:

Table 1. System objectives

	System objective	Stakeholder
1	Deliver the nominated gas volume at correct pressure, quantity and time	Gas customers
2	Provide healthy and living conditions and unaffected natural environment in the relevant geographical area	Society
3	Allow affordable profit	System owners
4	Transport gas from production terminals to exit terminals	Shippers

Requirements

Immediately following the analysis of objectives is the translation into requirements. The requirements are technical descriptions of system characteristics, specified in the form of a quantitative measure that can be verified, but they do not provide specific solutions.

Table 2 presents a partial list of the resulting requirements to satisfy the previously presented

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[7] Each stakeholder is given a number for later analysis of stakeholder interactions, see Figure 5.

[8] A technical service provider is a company, which has an agreement with the system operator for the operation of pipelines, terminals, platforms or other technical facilities.

objectives. The stated operational values represent typical operation[9].

Table 2: System requirements

	System requirement
1a	Obtain a deliverability of 99% over a year
1b	Each system exit point shall have the capability to meet daily fluctuations versus total customer demand, *q*, according to the formula: $a + bq + cq^2 + dq^3$
2a	CO_2 emissions from facilities at processing terminals shall not exceed 1565000 tonnes/year (SFT 2007)
2b	NO_x emissions from facilities at processing terminals shall not exceed 1736 tonnes/year (SFT 2007)
2c	SO_2 emissions from facilities at processing terminals shall not exceed 4.5 tonnes/year (SFT 2007)
2d	Noise level at the processing terminals' nearest house shall not exceed 50 dBa (SFT 2007)
3a	Specific power consumption[a] for system compressor stations shall not exceed 28.0 Wh/scm
3b	Operate the terminals with a production availability[b] of 97% over a year

a. Specific power consumption is a measure of system energy efficiency, and is calculated by dividing compressor power consumption with actual delivered gas into the export system.

b. Production availability is calculated by dividing delivered gas from a terminal by the sum of delivered gas and lost gas production due to unscheduled events.

Discussion of the requirements. The emission limits referred to in Table 2 are maximum values. According to the Norwegian Pollution Control Authority (SFT 2007), however, any pollution is undesirable. Even if the emissions from terminals comply with the emission limits, terminals have a duty to reduce the emissions as much as possible within reasonable costs. This also applies for emissions where no specific limits exist. Furthermore, the Ministry of Petroleum and Energy (MPE 2006) states that as a consequence of more energy efficient operation, a realistic and ambitious estimate for possible CO_2-emission reduction from the NCS is in the range of 5-10% within year 2020. The system should strive to achieve these reductions, although they are not specified in requirements. It is known to the system operators that reducing power consumption will reduce environmental emission in addition to reductions in the operating costs.

Some of the requirements may satisfy more than one objective. The requirements specified in 1a and 3b will also satisfy the shippers' objective –objective 4. Requirement 3a, which specifies a maximum limit for compressor power consumption may also partly satisfy the society's objective of an unaffected natural environment in the relevant geographical area. By keeping the required power for electrical driven compressors low enough, extension of the electricity grid may be avoided. Such an extension would imply intervention on the nature environment in the form of cables to the processing terminals placed in locations where a power cable might deteriorate the cultural experience of traditional Norwegian cultivated landscape. Fjords and untouched nature are some of the most important attractions in Norwegian tourism.

As previously stated, the SE process tasks are performed in an iterative manner. The quantitative measures that are specified in the requirements are not absolute. They may be changed as a result of validation of solution methods and evaluation of results and experiences by using the established models.

Search for solutions – the information models

Evaluation of the previously identified objectives and requirements reveals two categories of goals, which the gas export system must meet:

- satisfy customer nominations - delivery security
- minimize power consumption and environmental emissions - energy efficiency

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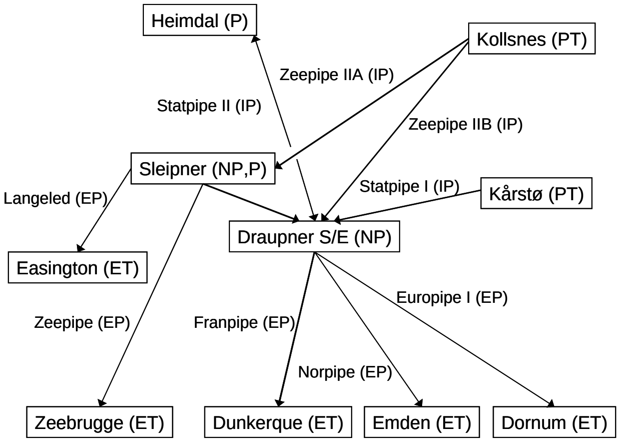
[9] The values may differ from real operational values which are confidential.

Decomposition and aggregation of the main problem and the corresponding system is necessary to understand and solve the problem and satisfy the objectives. The purpose of decomposition is to make each part manageable in size and complexity. This section presents several information models based on decomposition and aggregation that have been developed to analyse the main problem.

Architecture models. Figure 3 shows the natural gas export subsystem at the NCS subject for analysis. The context of the system is defined such that the system-of-interest only consists of the dry gas export subsystem at the NCS. The notations in Figure 3 show the function of each element in the figure.



Notations:

EP	Export pipeline - pipeline where the pipeline outlet is connected to an exit terminal
ET	Exit terminal - the point/terminal where the customer nomination will be delivered (and gas leaves the network)
IP	Intermediate pipeline - pipeline, which not terminates at an exit terminal
NP	Node platform - platform that connects more pipelines together
P	Production platform - platform where a production of gas occurs, and gas comes into the network
PT	Processing terminal - terminal where gas is processed and compressed and comes into the network

Figure 3. The natural gas export subsystem

The natural gas export system can be regarded as a system of systems (SoS), defined as an interoperating collection of component systems that produce results unachievable by the individual system alone (INCOSE 2006). SoS applies to a system-of-interest which typically entails large scale interdisciplinary problems with multiple, heterogeneous distributed systems.

Figure 4 illustrates an architecture model of the NDGES. The model shows how the system is physically built up from system elements and subsystems according to the previously described definitions. Each pipeline is connected to one plant at the pipeline inlet and one plant at the pipeline outlet.

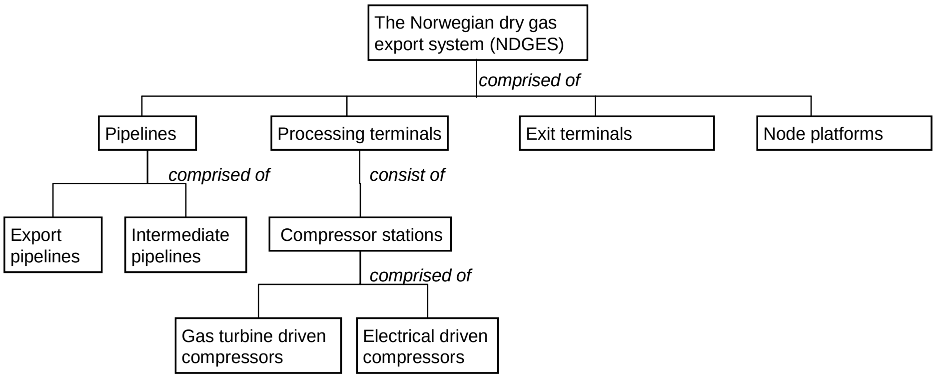


Figure 4. Model of the system elements and subsystems of the NDGES

Interaction chart. The n-squared interaction chart in Figure 5 identifies the system's administrative and physical interactions with its context. Each interaction is given a certain letter. The letters a-m represent administrative interactions, and n-r represent physical interactions. The numbers in the figure represent the stakeholders as identified previously. The chart should be read such that the outputs from lower-numbered stakeholders that are input to higher-numbered processes are indicated by a letter in the top diagonal. The outputs from higher-numbered stakeholders that are input to lower-numbered stakeholders are indicated by a letter in the lower diagonal. According to the chart, emissions are input to the society. Actually, the emissions are emitted to the natural environment. However, since natural environment is not identified as a separate stakeholder, the society is chosen to be the receiver of the emissions.

1	b,q		b,f	d	b,f	a,b,f	h,n	m,p
i	**2**	b						
	i	**3**						
a,b,c,n			**4**	n				p
d,n				**5**				p
b,c,e					**6**			
c,g,o						**7**	a	
h						j,r	**8**	
k,l								**9**

a.	availability
b.	reporting
c.	forecast
d.	operating agreement
e.	capacity
f.	instruction
g.	nomination
h.	nomination matching
i.	regulation
j.	order
k.	opinion
l.	request
m.	accountability
n.	gas
o.	tariff
p.	emission
q.	tax
r.	gas payment

Figure 5. N-squared interaction chart

The model illustrates that the gas export system's interactions with other systems in the system context are extensive. The interactions do not only include technical/physical aspects, but also involves economical and environmental considerations. Solutions of the main problem must take this into account. The partial CBA presented later identifies the costs and benefits associated with these interactions in operation of the system.

Input/output models. Each subsystem or system element in Figure 4 has a required function to perform. The functions can be represented by inputs and outputs to the subsystems/elements. Within the subsystems/elements the conversion from inlet data to outlet data can be represented by means of mathematical functions. These data must be quantified. Each of the subsystem/element also has certain properties which are used in the conversion from input and output data. The following model (Figure 6) shows input data, output data and the property of one system element – the compressor stations. The input data are divided in general variables and control variables. Control variables are those variables that typically will be varied in optimization of system operation. The general variables will be specified for each specific operating mode.

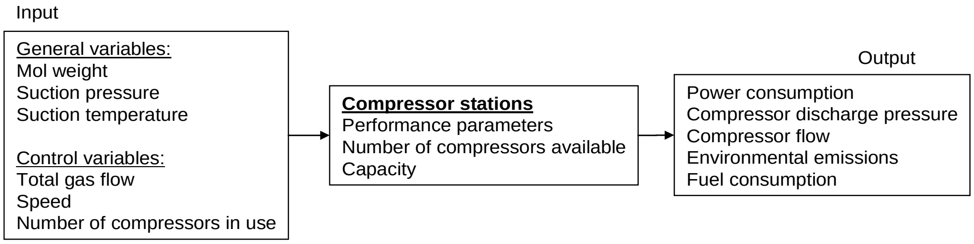


Figure 6. Input/output model for compressor stations

Solution method - optimization model. Optimization of gas export system operation is dependent on optimum operation of each system element and subsystem, but the elements must also operate optimally together. Optimum operation as regards solely gas delivery security implies a high pipeline inventory and this requires a high compressor discharge pressure. Compressing the gas to a high pressure results in increased power consumption, and thereby increased costs and emissions. Optimum operation as regards energy efficiency implies reducing compressor power consumption. This will inmost cases leads to reduced discharge pressure, reduced pipeline inventory, and thereby weakened ability to deliver gas to the customers. Furthermore, because of high export gas volumes, compressor stations must comprise several compressors in order to provide sufficient capacity. Each compressor has a favourable operating range as regards energy efficiency. However, the pipelines that are connected to the compressor station require a specific gas flow rate at a specific pressure, according to customer nominations. Therefore, each compressor may not be able to operate in its most efficient operating range. But this makes it important to operate them as efficient as possible together, and to avoid operating some compressors in a very unfavourable operating range.

The decomposition of large problems into sub-problems is necessary due to the complexity of the global problem and the need for various skills and methods to enable solution of the different sub-problems. Each of the sub-problem definitions must fit into the total problem solution. The integration of sub-problem solutions into a global solution is the essence of systems integration.

Figure 7 illustrates one possible high-level solution concept for the main problem - models of optimum operation of gas export systems. The main problem is decomposed into sub-problems, and each sub-problem relates to a system element or a subsystem as presented in Figure 4. The sub-problems identified for this work is defined in Figure A-2. A solution model is developed for each sub-problem. Figure 7 shows the relationships between these models, the system, system elements and subsystems, and the related problems and sub-problems. It also shows the tasks that must be done after model development – evaluation, validation and implementation.

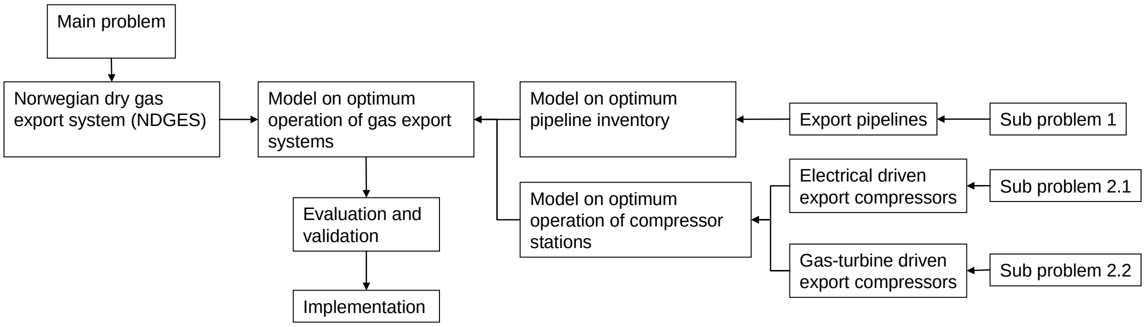


Figure 7. Relationships between sub-problems, system elements, subsystems and system-of interest and solution models.

In the model on optimum operation of gas export systems, the configuration of the optimal system operation will be determined as a result of minimization of the total specific power consumption. This result should correspond to maximum benefit to the stakeholders. (A schematic diagram on how the optimization model work is displayed in Figure A-3.)

An important aspect of the work is that the established models should provide results that can be implemented in strategic planning and operation of actual gas export systems. The models are therefore based on an actual gas export system, including all its physical components, and its actual properties, relationships, operational procedures and historical data. Furthermore, the system optimization models must take into account the constantly changing and highly uncertain nature of gas export operation (such as environmental compliance and gas demand).

Cost-benefit analysis.

As previously described, a CBA starts with description of the problem and the objective by initiating actions. These activities are comprised in the SE process described above, and will not be further examined in this section.

The different actions that are considered in this analysis in order to achieve optimum system operation are:

- continuing to operate like the current situation
- utilising the established system optimization model

The purpose of the analysis is to see if the obtained results by using the optimization model will provide a better way to operate the gas export system on the NCS than current operation, i.e., the two actions are compared in the analysis.

In the following a systematic identification and characterization of costs and benefits in operation of gas export systems is provided. The costs and benefits are associated with input and output to subsystem/system elements, and consider all stakeholders (the society as a whole) and the stakeholders' objectives. The work focuses on those costs and benefits which will differ between different operational ways.

Shortfall[10] costs. The main costs by changing operation of the gas export system are identified as shortfall costs. Optimizing system operation through minimization of specific power consumption may lead to lower pipeline inventory. Nomination increases or any system equipment shutdowns may result in shortfalls. To compensate for a shortfall, shippers may buy gas in the open market, so that the customers can receive their ordered gas amount. The short term gas price is therefore used to estimate this part of the shortfall costs.

If the gas customers don't receive the gas that they have ordered, this will also represent a cost to the society.

Shortfalls may also lead to poorer reputation for the shippers. This may result in gas price reduction in long term contracts, i.e. lower incomes to the shippers. It is assumed that the price reduction will be dependent on the size and number of shortfalls.

It should be noted that shortfalls are normally not lost gas. The gas may be sold at a later point of time. The present value of this, however, will be lower when compared to selling the gas today.

Main benefits. The main benefits by changing/optimizing operation of a gas export system are identified as reductions in operating costs and emissions.

Reductions in operating costs of electrical driven compressor. Optimization of system operation may result in lower pipeline inventory and thereby lower pipeline inlet pressure and lower compressor power consumption. Compressor power consumption may also be lower due to more favourable operating ranges for the compressors. This represents savings in energy costs. For electrical driven compressors the benefit will be represented by reduced electricity costs. The

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[10] Shortfall refers to an amount of gas which is not delivered to the customers in accordance with their nominations within a day.

electricity price is used to estimate this part of the savings. In the longer term, reduced electricity consumption may also lead to lower electricity price for the operator of the compressor stations.

Reduced electricity consumption may also benefit the local citizens, since more electricity could be available for local use. This benefit will only appear if there is a lack of energy in the area. As previously described, a potential extension of the electricity grid may then be avoided, thereby avoiding the associated cost, which could be large.

Reductions in operating costs of gas turbine compressor. Lower compressor power consumption means lower fuel costs for gas turbine driven compressors. The reduction will be dependent on which value the fuel cost should take. Typically, it will be much lower than the market gas price, since operation of the compressors will not decrease the present exported gas amount and with that the gas sale incomes. Consumption of a quantity of a non-renewable fuel gas precludes its use in the future, but the present value of this gas will be very low.

Reductions in emissions. Operation of gas turbine driven compressors, however, also results in emission of NO_X and CO_2. Reduction in fuel consumption leads to reduction in these emissions. Since there are taxes on these emissions, a reduction results in lower emission costs. In general, emissions lead to degradation of natural and man-made environments, including disrupting natural material, energy and biological balances, and they have negative consequences on human health and safety. Therefore, reduced emissions will also benefit the natural environment in the relevant geographical area, but this benefit is hard to express in monetary values. It requires an analysis and description of transport of the pollutants through various pathways to man. Factors that are involved in this process are for instance local meteorology, hydrology, pollutant re-concentration mechanisms, pollutant loss mechanisms, biological uptake mechanism, population distribution and life style. Human exposure levels and rates must then be assessed to determine dosage. Finally health damage corresponding to this dose must be evaluated and a monetary cost be assigned to the health damage. Efforts to assign values to such costs are highly preliminary, subjective and generally imperfect. (NSIC 1976) However, it is assumed that these costs are comprised in the emission taxes, and actual current values of these costs will represent the emission costs in this analysis.

Reduction in maintenance costs. More favourable operation of the compressors may results in reduced maintenance costs. Optimum operation will attempt to operate the compressor in their most efficient regime. This may results in less wear and thereby reduced maintenance costs. However, these costs are not quantified in the further analysis.

Numerical example. A numerical example of costs and benefits by optimizing system operation is presented in Table 3. Average export flow rates for the export pipelines and average gas production quantities over the last two years are applied as a basis for the example. Optimizing operation based on these values will recommend reduced pipeline inlet pressure compared to normal operation. Reduced pressure results in lower compressor power consumption. However, lower pressure may also imply a higher amount of total shortfall. Specific values of shortfall increase and pipeline pressure reduction are applied in the example.

The anticipated yearly costs and benefits by optimizing operation compared to typical operation are calculated. The calculation is based on typical values of gas and electricity prices and emission taxes. Included in the example are the costs and benefits described in the sections above. The savings in fuel costs for gas turbines are neglected. Reductions of CO_2 and NO_X emissions presented in the table are a function of fuel consumption. The reductions are derived from reductions in compressor power consumption, and are in accordance with actual gas turbine performance characteristics. Reductions in electricity costs are in accordance with actual performance characteristics of electrical motor driven compressors.

Shortfall costs are represented by the costs of buying the gas shortages in the open market. It is assumed that these costs will also represent costs to society and shippers if the nominated gas quantities are not delivered.

The table shows that operating according to optimization model recommendations yields a positive net value.

Table 3: Example of costs and benefits by modified system operation

Short term gas price	Euro 0.16/scm
Electricity price	Euro 0.06/kWh
CO_2 tax	Euro 0.10/scm fuel gas
NO_X tax	Euro 2.00/kg NO_X

Benefit				**Cost**	
Electricity costs (electrical driven compressors)		CO_2 and NO_x costs (gas turbine driven compressors)		Shortfall costs	
Number of small compressors, 1.0 MW reduction	4	Number of small compressors, 1.0 MW reduction	3	Yearly increase of shortfalls, Mscm	15
Number of large compressors, 2.0 MW reduction	6	Number of large compressors, 2.0 MW reduction	2	Yearly cost increase of shortfalls, Euro	2,400,000
Yearly reduction of compressor power consumption, kWh	140,160,000	Yearly reduction of fuel gas consumption, scm	14,348,880		
Yearly cost reduction of compressor power consumption, Euro	8,409,600	Yearly reduction of NOX-emissions, kg	113,151		
		Yearly cost reduction of CO_2 taxes el gas consumption, Euro	1,434,888		
		Yearly cost reduction of NOX taxes, Euro	226,302		

Total benefit, Euro	10,070790
Total cost, Euro	2,400,000
Net value, Euro	7,670,790

Sensitivity. CBA requires a prediction of the future. Precise predictions about the future are rarely possible to make. In a CBA, uncertainty about the magnitude of the impacts we predict and the values assigned to them will be present. The basic analysis usually submerges this uncertainty by using the most plausible estimates of the unknown quantities, as in the example above. Sensitivity analysis is a way of investigating the robustness of net benefit estimates to different resolutions of uncertainty. The purpose of sensitivity analysis is to determine how net benefit changes if important parameters deviate from their assumed values. A thorough sensitivity analysis will not be presented in this paper, but will be performed in later work. However, some aspects regards sensitivity related to this work is presented here.

The net value in the example is sensitive to variations in key parameters such as:

- gas price
- electricity price
- taxes on emissions
- reduced gas price due to poorer reputation

and to variations in operational variables such as:

- total customer nominations
- pipeline inlet pressure values
- expected shortfall (or actual amount of delivered gas)
- flow in the Statpipe I pipeline (see Figure 3), which represents the flexibility between Kollsnes and Kårstø

Variations in these parameters and variables will influence costs and benefits, and with that, the net value. The result of the CBA is therefore strongly dependent upon which values these parameters and variables take.

Especially, valuing environmental impacts is not easy. According to (Boardman et al. 2006), one reason for this is that each environment area is used for multiple purposes. Consequently, there are potential problems of aggregation and double counting. In this analysis it is assumed that the CO_2 and NO_X taxes bear all the costs associated with the CO_2 and NO_X emissions respectively. However, as stated in several studies, the costs related to these emissions are many, so the value of this cost should may be set much higher than today’s taxes. (Andersen 1995), for instance, states that the rates of emission taxes are not set so as to match the true environmental costs or to assure specific environmental targets, and are generally much too low.

Discussion and further work

The purpose of the paper was to present ways that SE principles and models have been applied in order to analyse and develop models of optimum operation of gas export systems, with a focus on the NDGES. SE has proven to be a very appropriate tool for conducting an analysis and overcome the complexity of the main problem since the focus in SE is on analysis, understanding and optimization of structure and interfaces in large integrated systems with many elements and subsystems. This typically describes the gas export system on the NCS.

The NDGES is a typical one-of-a-kind, unique development, and does not involve design of new systems. The focus is, therefore, on ensuring optimum integration and operation of the technology and equipment that are used.

Information models are established, and they give a good overview of all the elements and subsystems in the system and the system context, and how they are related to each other. Furthermore, the models describe input and output data of the elements and subsystems. The overall optimization model is based on these data and the relations between them.

The information models are part of a SE process that has been used to identify where changes in operation may take place and to analyse the main problem for subsequent optimization. This paper has not presented details around each task in the SE process. However, it has identified the tasks to be performed for the system-of-interest, and concentrated on describing a high-level overview.

The work has also performed a partial CBA comprising identification and characterization of costs and benefits of modification in gas export operation. Disadvantages with such an analysis is that the result may be highly uncertain, input data required for performing a CBA are often incomplete and the analysis is often unable to properly account for the societal distribution of costs and benefits. Limitations are associated especially with valuing human health and potential damage to natural resources.

The conditions of gas export systems are constantly changing and highly uncertain, and the models must account for this uncertainty. Therefore, it is of importance to evaluate and validate both the optimization models and the analyses to ensure that they provide results that can be implemented in strategic planning and operation of actual gas export systems. In the evaluation, a thorough sensitivity analysis of changes in key parameters and variables will be performed.

The tasks in the SE process and CBA related to solving the problem, validating the models and solutions and implementing the results in operation will follow in later work. However, some aspects and considerations about these tasks have been presented in this paper.

Conclusion

The SE discipline is a useful tool for analysing and solving the main problem, which implies operation of a complex system. Development of information models has provided an overview of how objectives, requirements and system elements and subsystems are related to each other, and where modifications in operation can take place. Further, this work has described how SE is applied in order to structure the main problem, identify the different sub-problems and how they are related to physical system components. Solution of the sub-problems are developed, and presented in previous works. SE is applied in order to aggregate sub-solution models into a solution concept of the main problem. The structure of the main solution is presented in this work. The chosen solution is an optimization model for gas export systems. A characterization of which costs and benefits arise by changing the system operation and how those changes affect stakeholders was performed in a partial CBA.

Development of an overall optimization model for gas export systems, guidelines based on the model and validation of these is subject to the author's PhD-study.

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Biography

Vibeke Stærkebye Nørstebø is a PhD-student at the Department of Energy and Process Engineering at the Norwegian University of Science and Technology (NTNU). Her research is about optimum operation of gas export systems, with focus on the Norwegian gas export system. She received a master of science degree in industrial economics and technology management at NTNU in 2004.

Appendix

Figure A-1. The gas transport system on the NCS [MPE 2007]

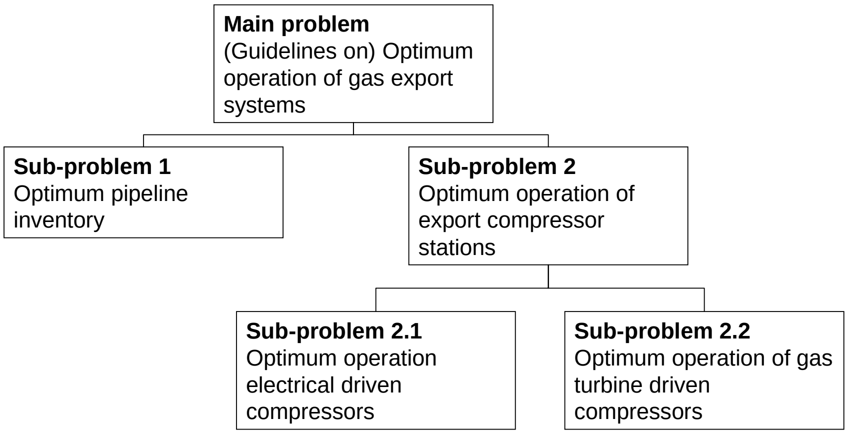

Figure A-2. System main problem and sub-problems

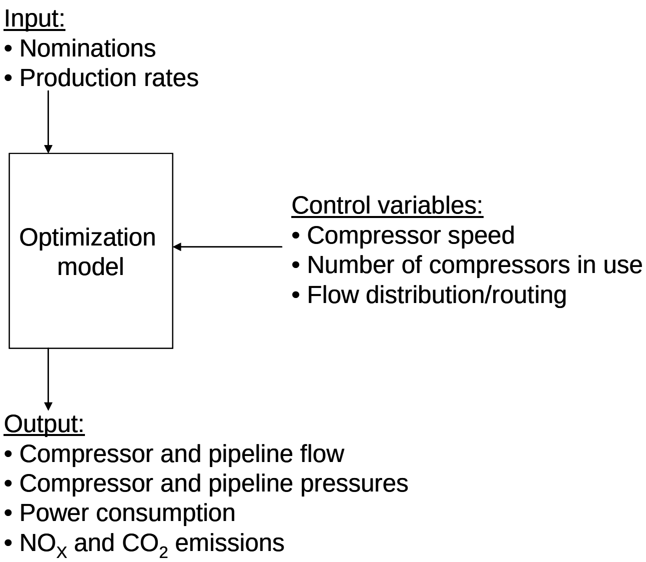

Figure A-3. Functional diagram of the optimization model

Appendix F Paper VI on Modell validation

Nørstebø, V.S., Paulsen, E.A., and Bakken, L.E., 2008,
“Optimum Operation of Gas Export System - Modell Validation”,
Paper No. IPC2008-64080, Proc. ASME International Pipeline Conference 2008, CA-Calgary, Alberta.

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Appendix G Pipeline inventory and gas flow equations

G.1 Pipeline gas flow equations

Assumptions

Gas transport in a pipeline is described by a system of partial differential equations: the continuity equation, the momentum equation and the energy equation, as well as the thermodynamic state equation of gas. Since pipelines on the NCS lie deep beneath the sea, with nearly constant ambient temperature, general simulation models do not take the energy equation into account. This is therefore neglected and the ambient temperature T is assumed to be constant. The other equations are presented in the following sections. Furthermore, the following assumptions are applied in the development of equations for gas flow in pipelines, in accordance with Wylie and Streeter [78]:

- Pipeline flow is isothermal.
- Expansion of the pipeline wall may be neglected.
- The pipeline has a constant slope over any particular reach.
- The pipeline has a constant cross-sectional area.
- The equation of state is given by $p = Z\rho RT$, in which the gas compressibility. factor, Z, is considered to be constant over the range of a single incident.
- One-dimensional gas flow relations are used.
- The friction factor is a function of Reynolds number and pipeline wall roughness. (Steady-state values are used in transient calculations.)
- Gas velocity, v, is much smaller than the acoustic wavespeed, c, so that $\frac{v}{c} \ll 1$.
- The change in kinetic energy along a pipeline may be neglected.

Equation of state

The equation of state is given by:

$$p = z\rho RT \quad , \tag{38}$$

where p and T are absolute pressure and temperature. The compressibility factor, z, characterises the non-ideal behaviour of gas and is a function of pressure and temperature. For any given incident, an average value of z is generally used. Given the above mentioned assumptions of constant temperature, T, the equation of state can be related to the acoustic wavespeed, c, as follows [78]:

$$c = \sqrt{\left(\frac{p}{\rho}\right)} = \sqrt{(zRT)} \tag{39}$$

The continuity equation

The continuity equation expresses mass conservation. The net mass flow into a segment of pipeline with length dx equals the time rate of mass increase within the same pipeline segment. By applying the relationship between mass flow, and gas velocity known as

$$\dot{m} = \rho \cdot v \cdot A, \tag{40}$$

the continuity equation can be expressed as:

$$-\frac{\delta(\rho v)}{\delta x} = \frac{\delta \rho}{\delta t} \tag{41}$$

Equation (39) can be expressed as:

$$p = c^2 \cdot \rho \tag{42}$$

By employing this relationship, Eq. (41) can also be expressed as:

$$\frac{c^2}{A} \cdot \frac{\delta \dot{m}}{\delta x} + \frac{\delta p}{\delta t} = 0 \tag{43}$$

The momentum equation

The momentum equation relates the sum of external forces acting on a fluid element to its acceleration, or to the rate of change of momentum in the direction of the resultant external force. For one-dimensional flow, this can be written as:

$$\sum F_x = \frac{d}{dt}(mv) = \frac{\delta}{\delta t}(\rho \cdot A \cdot v) \cdot dx + \frac{\delta}{\delta x}(\rho \cdot A \cdot v^2) \cdot dx, \tag{44}$$

where

$$\frac{dv}{dt} = \frac{\delta v}{\delta t} + v \cdot \frac{\delta v}{\delta x} \tag{45}$$

Three types of forces affect an element with cross-sectional area A, length δx and mass $m = \rho \cdot A \cdot dx$. These forces are F_p, which represents pressure loss over the element, gravity force, F_g, and the friction force, F_f. Figure G–1 illustrates these forces. According to the figure, the forces can be expressed as:

$$F_p = pA - \left(p + \frac{\delta p}{\delta x} \cdot dx\right) \cdot A = -\frac{\delta p}{\delta x} \cdot A \cdot dx \tag{46}$$

$$F_g = -m \cdot g \cdot \sin\theta = -\rho \cdot g \cdot A \cdot dx \cdot \sin\theta \tag{47}$$

$$F_f = \tau_0 \cdot \pi \cdot D \cdot dx \tag{48}$$

Shear stress, τ_0, can also be described by the Darcy-Weisbach equation, $\tau_0 = \frac{\rho \cdot f \cdot v^2}{8}$, where f is the Darcy-Weisbach friction factor. Since the area A equals $\pi \cdot \frac{D^2}{4}$, Eq. (48) can also be written as:

$$F_f = \frac{\rho \cdot v^2 \cdot f \cdot D \cdot dx}{8} = \frac{\rho \cdot A \cdot v^2 \cdot f}{2} \cdot \frac{dx}{D} \tag{49}$$

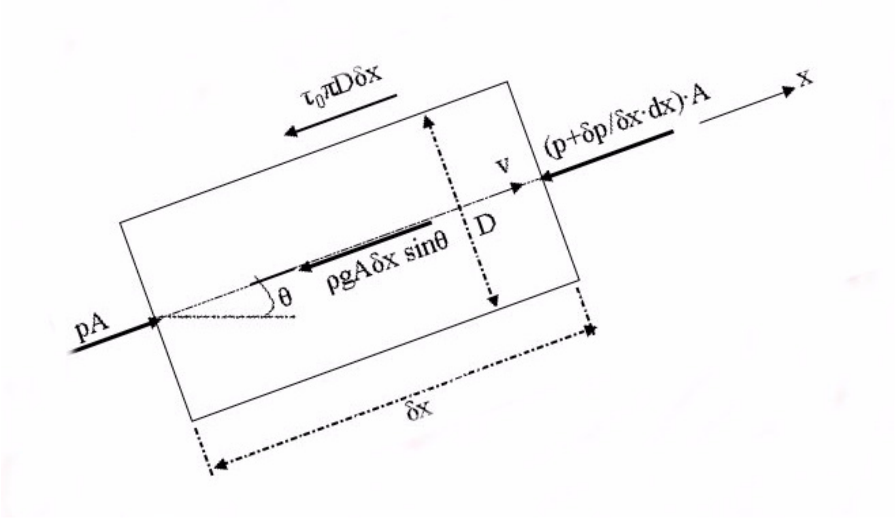

Figure G–1: External forces on a fluid element

By combining Eqs. (44)-(49) and dividing by $A \cdot dx$ the following expression describes mass conservation:

$$\frac{\delta}{\delta t}(\rho \cdot v) + \frac{\delta}{\delta x}(\rho \cdot v^2) + \frac{\delta p}{\delta x} - \frac{\rho \cdot v^2 \cdot f}{2 \cdot D} + \rho \cdot g \cdot \sin\theta = 0 \tag{50}$$

Because the pipelines are assumed to be horizontal, the gravity term will fall out. Since $\frac{v}{c} \ll 1$ and $c = \sqrt{\left(\frac{p}{\rho}\right)}$, the second term in the equation above ($\frac{\delta}{\delta x}(\rho \cdot v^2)$) will also be ignored. Eq. (50) can be expressed as:

$$\frac{\delta p}{\delta x}+\frac{1}{A}\cdot\frac{\delta\dot{m}}{\delta t}-\frac{f\cdot c^2\cdot\dot{m}^2}{2\cdot D\cdot A^2\cdot p} = 0\text{, or }\frac{\delta p}{\delta x}+\frac{\delta}{\delta t}(\rho\cdot v)-\frac{f\cdot\rho\cdot v^2}{2\cdot D} = 0 \qquad (51)$$

[78]

Steady state equations

For steady-state isothermal flow, $\dot{m}$ is constant, and $\frac{\delta\dot{m}}{\delta t}$ equals zero. In addition, the pressure as a function of time will be constant [78]. By integrating the equation for a pipeline with length L, and applying the relationship $\dot{m} = \rho\cdot Q$, Eq. (52) appears. This equation describes the relationship between pipeline gas flow and inlet and discharge pipeline pressure.

$$\frac{dp}{dx} = \frac{f\cdot c^2\cdot\dot{m}^2}{2\cdot D\cdot A^2\cdot p} = \frac{f\cdot c^2\cdot\rho^2\cdot Q^2}{2\cdot D\cdot A^2\cdot p} \quad \text{<=>}$$

$$p\cdot\frac{dp}{dx} = \frac{f\cdot c^2\cdot\rho^2\cdot Q^2}{2\cdot D\cdot A^2} \quad \text{<=>}$$

$$\int_0^L\left(p\cdot\frac{dp}{dx}\right)dx = \int_0^L\left(\frac{f\cdot c^2\cdot\rho^2\cdot Q^2}{2\cdot D\cdot A^2}\right)dx \quad \text{<=>}$$

$$\frac{(p(L))^2-(p(0))^2}{2} = \frac{f\cdot c^2\cdot\rho^2\cdot Q^2}{2\cdot D\cdot A^2}\cdot L \quad \text{<=>}$$

$$-(p_d^2-p_i^2) = \frac{16\cdot f\cdot c^2\cdot\rho^2\cdot L}{\pi^2\cdot D^5}\cdot Q^2 \quad \text{<=>}$$

$$Q^2 = \frac{\pi^2\cdot D^5}{16\cdot f\cdot c^2\cdot\rho^2\cdot L}\cdot(p_i^2-p_d^2) \quad \text{<=>}$$

$$\dot{m}^2 = A\cdot\sqrt{\frac{MW}{Z\cdot R_0\cdot T}\cdot(p_i^2-p_d^2)\cdot\frac{1}{f}\cdot\frac{D}{L}} \qquad (52)$$

For gas flow at standard conditions, Eq. (52) may also be written as:

$$Q_{std} = \frac{\pi\cdot T_{std}}{4\cdot p_{std}}\cdot\sqrt{\frac{(p_i^2-p_d^2)\cdot D^5\cdot R_0}{MW\cdot T\cdot Z\cdot L\cdot f}}, \qquad (53)$$

For a certain gas in a specific pipeline, the equation of gas volume flow at standard conditions Eq. (53)) can be simplified to:

$$Q_{std} = k \cdot \sqrt{p_i^2 - p_d^2} \tag{54}$$

In the equation, k is a constant which represents pipeline length and diameter, gas molecular weight, temperature along the pipeline, compressibility factor, friction factor, and the constant numbers (T_{std}, p_{std}, R_0.

In this work, the simulations performed in Pipeline Studio, are based on the following choices for the gas flow:

- BWRS equation of state
- Constant sea temperature equal to October average temperature[1]
- Colebrook-White friction factor: $\frac{1}{\sqrt{f}} = -2 \cdot \ln\left(\frac{2{,}51}{Re \cdot \sqrt{f}} + \frac{\varepsilon}{3{,}71 \cdot D}\right)$
- Lee, Gonzales and Eakin’s empirical correlation of viscosity

G.2 Pipeline inventory calculations

In order to calculate pipeline inventory, I, at standard conditions, the pipeline gas volume (inventory) at standard conditions must be related to the pipeline volume at actual conditions:

$$\left(\frac{p \cdot V}{Z \cdot R \cdot T}\right)_{pipe} = \left(\frac{p \cdot I}{Z \cdot R \cdot T}\right)_{std} \tag{55}$$

The gas constant, R, will be the same both in actual pipeline and standard conditions, the compressibility factor, Z_{std}, equals 1 in standard conditions. Pipeline inventory, I, can therefore be described as:

$$I = \frac{p_{pipe}}{p_{std}} \cdot \frac{T_{std}}{T_{pipe}} \cdot \frac{V_{pipe}}{Z_{pipe}} \tag{56}$$

Pipeline pressure, p_{pipe}, temperature, T_{pipe}, and compressibility factor, Z_{pipe}, vary with pipeline length, and pipeline inventory is calculated by integrating over the whole length.

Goslinga et al [33], among others, describe pipeline inventory by the following equation:

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1) October is considered the month with the warmest sea temperature, and thus the one in which the gas reaches its lowest density. The maximum and minimum limits in the pipeline inventory envelopes, and the operational margins may therefore be wider than the calculated limits. Because of this assumption, some empirical operational inventory points may lie outside the calculated pipeline inventory envelope.

$$I = C \cdot \frac{L \cdot D^2}{Z \cdot T} \cdot p_{avg} \tag{57}$$

where

$$C = \frac{\pi}{4} \cdot \frac{1}{10^6} \cdot \frac{T_{std}}{p_{std}}, \tag{58}$$

$$V_{pipe} = \frac{\pi \cdot D^2}{2} \cdot L, \tag{59}$$

$$p_{avg} = \frac{1}{2} \cdot (p_i + p_d), \tag{60}$$

and T and Z are assumed to be constant over the pipeline length.

This average pressure value p_{avg}, does not represent the real pressure distribution in a pipeline and will underestimate pipeline inventory as illustrated for Europipe II in Fig. G-1. The area below the red curve represents actual pipeline inventory, while the area below the green curve represents inventory calculated in accordance with Eqs. (57)-(60). However, the approximation is commonly utilised and assumed to represent pipeline inventory satisfactorily. For the pipeline and conditions represented in Fig. G-1, the difference will be approximately 1%.

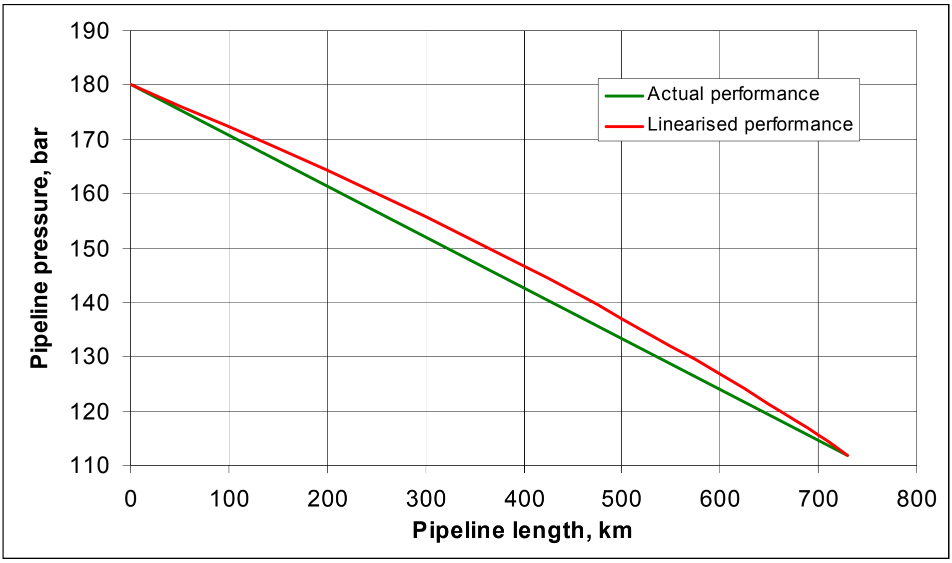

Figure G–2: Pipeline pressure as a function of pipeline length

Appendix H Booking and shipping system on the NCS

This section will describe the basic routines and procedures related to technical and economic aspects of gas transport. The routines and procedures for communication between the shippers and the gas export system operator (Gassco) are described in the Shipper Manual [26].

H.1 Participants in the shipping system

Participants in the Shipper Manual are the system operator, shippers, field operators, downstream transport system operators (DTSOs), technical service providers (TSPs) and upstream pipeline operators. The system operator is responsible for coordinating gas transport, all communication with fields and terminals, correct ownership allocation and determination of gas quantities for tariff purposes. Shippers are owners of gas tendered for shipment in the export system. Field operators deliver gas into the system and interact with the system operator either directly or via an upstream pipeline operator. DTSOs are responsible for operating and maintaining the transport system downstream of the Gassco-operated transport system. TSPs have signed a technical service agreement with the system operator to run riser platforms, terminals and plants within the system. Upstream pipeline operators are responsible for upstream pipelines connected to the system-of-interest. Figure H–1 illustrates these relationships.

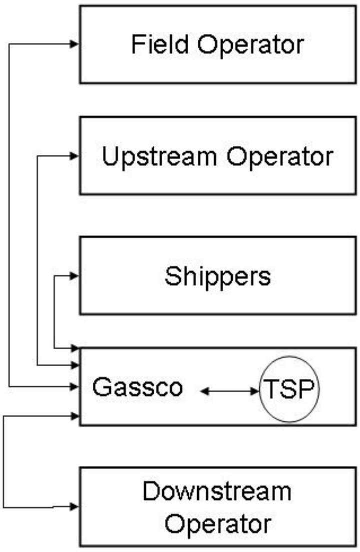

Figure H–1: Participants in the Shipper Manual and their relationships

H.2 Operating principles and terms

The operating principles for the export system are based on some specific terms which are relevant for establishing guidelines for system operation and will be briefly described below. These are availability, nominations, instructions, matching and balancing.

Availability

Gassco inform shippers about the quantities available to them on the fields and transport capacity available at each exit point. In other words, field operators and TSPs must notify Gassco of the delivery capacity for their respective fields and terminals. Gassco will calculate each shipper's minimum and maximum opportunities for lifting dry gas from each field.

Nominations

Shippers nominate quantities to be delivered at exit terminals and from fields towards Gassco. Nominations are made weekly and within each day. The sum of daily nominations for the system entry points must match the sum for the exit terminals. Each shipper's exit terminal nominations must be equal to or less than their capacity rights at each relevant exit terminal. The exit terminal nomination must identify the receiving downstream shipper(s) and corresponding quantities.

Instructions

Gassco will issue instructions to fields and TSPs regarding physical deliveries from the fields and terminals. On the basis of shipper nominations, Gassco will perform the necessary checks. Furthermore, Gassco will include necessary adjustments in order to bring physical deliveries as close to nominations as possible (gross calorific value (GCV) corrections).

Matching

Gassco will match shipper nominations at each exit terminals against the relevant DTSO. Re-nomination will take place if the nominations do not match.

Balancing

Gassco will reconcile actual deliveries at the exit terminal with nominated deliveries and make sure that any imbalances are settled. Owing to variances in such elements as gas quality and metering accuracy, actual physical deliveries will vary from nominated quantities.

Other operational principles

Gassco will operate the system with due regard to operational tolerances and a sufficient working quantity of gas (inventory) to accommodate shipper requirements for deliveries, changes in daily requirements, variations in flow rates, survival time in the case of unplanned events, gas quality and quality blending, pressure harmonisation, maintenance, capacity tests and energy optimisation.

Operation of the export system carefully considers gas nominations at the network's exit points. Continental European and British customers enter into sale contracts with shippers. These contracts can be long-term agreements lasting for decades or short-term spot deals. Shippers nominate quantities to be lifted from production fields and delivered at exit terminals. Nominations are made weekly and within each day. Each shipper's exit point nominations must be equal to or smaller than its transport capacity rights. Furthermore, exit point nominations must match customer and lifting nominations. On the basis of shipper nominations, the system operator will give instructions to the operators of gas treatment and processing plants, such as Kårstø and Kollsnes, on the quantity of gas to be processed and delivered into the system.

The exit terminals have minimum pressure constraints which must be met. If gas is delivered at minimum pressure, no flexibility exists for making changes in pipeline flow. This means that increases in pipeline discharge flow are impossible, and that discharge flow could not be maintained should pipeline inlet flow decline. Under normal operating conditions, pipeline discharge pressure will therefore lie somewhat above the minimum pressure. The entry points have maximum pressure constraints which must not be exceeded.

The business side quite often works in gas energy, while the production side works in volumes. This implies that all customer nominations are made in energy (J) and all capacity bookings are made in volume (scm). A conversion between the two values must therefore be made. The factor to be used in the conversion between energy and volume is GCV. A typical gas sales agreement with a European customer imposes restrictions on how much the GCV value may vary. Gassco will publish the GCV value which each field produces once a year. This value will be an average for that field, and will be used for a complete year. Gassco will always check the customer nomination against the capacity booking for each shipper using the published GCV values.

H.3 Forecasts

To be able to predict offtake from the producing fields and requirements for gas transport on a long- and medium-term basis, shippers must provide Gassco with long-term, monthly and weekly forecasts. Made on a semi-annual basis, these long-term forecasts include an overview of the expected monthly quantity and quality of gas to be lifted for the current and next contract year.

Monthly forecasts include a six-month rolling availability and gas quality forecast for each field, showing the minimum and maximum technical capacity and expected daily deliveries in scm/d for each month. Every month, the TSPs must provide Gassco with a six-month rolling availability forecast for their terminal(s), showing the minimum and maximum technical capacity in scm/d for each month. Shippers must provide monthly a six-month rolling lifting forecast, showing the average daily lifting requirement for dry gas equivalent in GJ/d.

Weekly, shippers will provide a forecast of their anticipated gas sales at exit terminals. They must also provide a lifting nomination forecast consistent with anticipated gas sale volumes each week. On the basis of shipper forecasts of weekly lifting nominations, Gassco sends a weekly forecast to relevant field operators and TSPs.

H.4 Nominations and bookings

Shippers individually nominate to Gassco the quantities to be lifted from fields, bilateral transactions and shipper imbalances. All quantities will be nominated as energy units. The sum of each shipper's lifting nomination must equal the sum of their exit terminal nominations, adjusted for bilateral transactions and shipper imbalances. If these quantities do not match, Gassco is entitled to request the shipper to re-nominate. The nominations must not exceed the shipper's capacity rights. Exit terminal nominations will be given before each day and, when required, revised during the day. Unless agreed with the operator, the shipper is not be entitled to nominate gas deliveries at an uneven flow rate throughout the day.

The first shipper nomination deadline is 16 hours before the following day begins. The second shipper nomination deadline is 14 hours before the following day. If the shipper, after the second nomination deadline, makes a re-nomination, then Gassco will make reasonable efforts to accept this re-nomination. Each re-nomination must take place a minimum of two hours before the effective hour, providing changes can be accommodated within technical and operational limits. This implies that there may in some cases be a relatively short time span between the nomination and the actual movement of gas. This necessitates the ability to respond to business and events in a real-time manner, for instance by holding a pipeline inventory.

Routines for booking transport capacity between shippers and Gassco are described in the Booking Manual [28]. Time periods available for primary booking are long-term, medium-term and short-term, including within a day. There will first be an initial booking for allocation of capacities, except for within a day. Should spare capacity be available after the initial booking, an opportunity will exist to book on a first-come first-served basis for medium-term and short-term bookings. All bookings within a day are on a first-come first-served basis. Any forward period will be made available in a long-term booking window before the medium-term booking window and in a medium-term booking window before the short-term booking window.

Long-term capacity bookings reserve constant daily transport and/or processing capacity for whole gas year(s). Daily transport and/or processing capacity must be constant within a gas year. The initial long-term booking window will be open twice a year.

Medium-term capacity bookings reserve constant daily transport and/or processing capacity for whole calendar month(s). The initial medium-term booking window will also be open twice a yearat the same time as the long-term booking window.

Short-term capacity bookings reserve constant daily transport and/or processing capacity for one or more day(s). Short-term capacity can be separated into short-term capacity booked the day and within the day. Principles and procedures for booking capacity rights are presented in greater detail in Nørstebø [59].