RIGA TECHNICAL UNIVERSITY
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ASSESSMENT OF NATURAL GAS SUPPLY SYSTEM SECURITY

Summary of the Doctoral Thesis

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DOCTORAL THESIS
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To be granted the scientific degree of Doctor of Engineering Sciences, the present Doctoral Thesis will be publicly defended on 18 January 2016 at Riga Technical University, Faculty of Civil Engineering, Kipsalas Street 6B, Room 250.

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DECLARATION OF ACADEMIC INTEGRITY

I hereby declare that the Doctoral Thesis submitted for the review to Riga Technical University for the promotion to the scientific degree of Doctor of Engineering Sciences is my own and does not contain any unacknowledged material from any source. I confirm that this Thesis has not been submitted to any other university for the promotion to any other scientific degree.

Indra Niedrite ……………………………. (Signature)

Date: ………………………

The Doctoral Thesis has been written in Latvian. It includes Introduction, 3 Chapters, Conclusions, and Bibliography with 98 reference sources. The Doctoral Thesis has been illustrated by 44 figures. The volume of the Thesis is 109 pages.

ABSTRACT

The integral basic component of any state economy is the energy sector; therefore, energy security plays an important role in a national security guarantee. Natural gas supply disruptions would disturb both the industrial and household sectors; thus, precise security level assessment of natural gas supply system becomes more acute.

The aim of the Doctoral Thesis is to elaborate the security assessment methodology of a natural gas supply system.

Examining the notion of security of energy supply, it can be stated that there is a lack of joint understanding and any approach to the explanation of this concept; thus, the definition of security of natural gas supply has been formulated in this Doctoral Thesis. The results of the analysis reveal that security of natural gas supply is defined using differing concept-based techniques and various indicators, yet being not interrelated, which specifies the lack of the uniform methodology. According to the definition formulated in the Doctoral Thesis, as well as to the principles of the theory of constraints, N-1 infrastructure standard was identified as the minimum security indicator of natural gas supply system.

Based on the allocation of natural gas flows in the common Baltic natural gas supply system elaborated in the Doctoral Thesis for the cases of natural gas supply disruptions, it was concluded that N-1 infrastructure standard had significant shortcomings. Furthermore, the necessary amendments to the calculation formula for N-1 infrastructure standard were stipulated.

The minimum security assessment methodology of natural gas supply system was stipulated in the Doctoral Thesis and used to define the sufficiency of natural gas supply infrastructure in cases of natural gas supply disruptions, preventing the possible negative impact on consumers. The methodology is flexible, easy adaptable and applicable to all countries regardless of the scale of their natural gas supply system; it can also be applied in other sectors of energy industries, specifically, in power or heat supply.

The elaborated and verified minimum security assessment methodology of natural gas supply system will allow estimating sufficiency of natural gas supply infrastructure in cases of natural gas supply disruptions and will provide fast decision making on alternative sources of natural gas or necessary co-operation in organising natural gas flows, thus reducing the disruption risks of natural gas supply.

The results of the Doctoral Thesis have been reported at 14 international conferences and reflected in 8 publications.

TABLE OF CONTENTS

INTRODUCTION

To achieve long-term state and energy strategic goals, one of basic conditions is diversification of energy sources and security of energy supplies.

For a long time, the core objectives of the European Union's (hereafter – EU) energy policies are competitiveness, sustainability and security of supply. In February 2015, the EU Commission launched work on the European Energy Union. Security of supply is defined as one of five European Energy Union's strategy vectors.

Natural gas takes an essential part in the EU energy balance as it makes approximately 25 % of primary energy source consumption, and it is used mainly for electricity and heat production, as a raw material in manufacturing sector and as fuel in transport.

Natural gas is an important resource for the Latvian economy and energy system, and it plays an important role in the energy conversion sector – production of heat and electricity. The largest consumer of natural gas in Latvia is JSC “Latvenergo”, which uses natural gas mainly for combined heat and power production. Thus, disruptions in natural gas supply system would impact both the industrial and household sectors. Natural gas supply is one of the national security issues. That is why security of natural gas supply and the necessity of more precise assessment of risks of possible disruptions become increasingly acute. In the assessment of natural gas supply system security, EU natural gas supply system security standards are used in Latvia. Still these standards do not cover to a full extent the specifics of the Latvian situation. Furthermore, in the assessment of security of natural gas supply differing concept-based techniques and different indicators are used that demonstrate the lack of the uniform methodology. Therefore, it is necessary to estimate the possible tools and activities to minimise the risks associated with natural gas supply being significant for Latvia.

The aim of the Doctoral Thesis is to elaborate the security assessment methodology of natural gas supply system.

The tasks of the Doctoral Thesis:

1) To analyse techniques of security assessment of natural gas supply system.
2) To analyze security assessment indicators of natural gas system and elaborate the indicator of minimum security for natural gas supply system.
3) To calculate the steady-state operation of Latvian natural gas transmission system and model natural gas transmission system operations (natural gas flows) in cases of disruptions in natural gas supply.
4) To elaborate the minimum security assessment methodology of natural gas supply system, which defines sufficiency of natural gas supply infrastructure in cases of natural gas disruptions.

Scientific Novelty and Main Results

1) The minimum security assessment methodology of natural gas supply system has been elaborated, which defines sufficiency of natural gas supply infrastructure in cases of natural gas disruptions, eliminating a possible negative impact on consumers.
2) The model of practical application of Eliyahu Goldratt’s Theory of Constraints has been elaborated for security assessment of natural gas supply system that can also be applied to determine other energy source supply system security.
3) The definition of security of natural gas supply has been elaborated. Proprietary appraisal of security of energy supply concept confirmed the lack of the joint approach

to understanding and explanation of the concept. Considering specifics of natural gas supply and risks associated with natural gas supply, the author considers security of natural gas supply to be the ability of national natural gas supply system to meet the demands of natural gas end users in case of natural gas supply disruption.

4) The author suggests using a set of interrelated values for assessment of security of energy supply. The results of the analysis reveal that that security of natural gas supply is assessed using differing concept-based techniques and different, yet being not interrelated, indicators.

Practical Significance of the Thesis

The elaborated and verified minimum security assessment methodology of natural gas supply system will:

1) allow assessing sufficiency of natural gas supply infrastructure in cases of natural gas supply disruptions, eliminating a negative impact on consumers;
2) allow estimating the state-of-the-art situation for more than one state, as well as defining the interaction and relationship with natural gas supply systems in other countries;
3) provide fast decision making on alternative natural gas supply sources or necessary co-operation in rearrangement of natural gas flows, minimising risks of natural gas supply disruption.

The elaborated minimum security assessment methodology of natural gas supply system is based on the existing knowledge on assessment of security of energy supply. The methodology is relatively easy adaptable and applicable to other countries regardless of the current size of natural gas supply systems in these countries. The methodology can also be applied to power and heat supply systems.

Approbation of the Results of the Doctoral Thesis

The results of the Doctoral Thesis have been reported at 14 international conferences and reflected in 18 publications. The most significant findings of the Doctoral Thesis were presented at the meeting of the Latvian National Committee of World Energy Council on 6 July 2016, receiving a positive assessment.

The author has verified and applied the minimum security assessment methodology of natural gas supply system, during preparation of risk assessment of Latvian security of natural gas supply according to the requirements of Regulation (EU) No. 994/2010 of the European Parliament and of the Council of 20 October 2010 concerning measures to safeguard security of gas supply and the repealed Council Directive 2004/67/EC (hereafter – regulation No. 994/2010) approved by Decree No. 98 of the State Secretary of Ministry of Economics of the

Republic of Latvia as of 23 May 2013, as well as the updated security risk assessment of Latvia's natural gas supply approved by Decree No. 184 of the State Secretary of Ministry of Economics of the Republic of Latvia as of 22 July 2015. Furthermore, the minimum security assessment methodology of natural gas supply system is used in joint risk assessment of security of gas supply of Estonia, Latvia and Lithuania, which was approved by the Ministry of Energy of the Republic of Lithuania, the Ministry of Economics of the Republic of Latvia and the Ministry of Economic Affairs and Communications of the Republic of Estonia under the covenant concluded in September, 2012. Besides, the author has used the methodology for the preparation of the Amendments to the Energy Law (adopted by the Saeima on 11 February 2016), which establishes the liberalised natural gas market regulation in Latvia, as well as for the development of other natural gas market regulations.

1. TRENDS IN RISK ASSESSMENT OF NATURAL GAS SUPPLY CHAIN

1.1. Risks of Natural Gas Supply Chain

Risk is inevitable and faced in all individual and social day-to-day activities. Different factors may be considered as possible hazards or risks that can intentionally or unintentionally cause disruptions in the power supply chain. Assessing risks of power supply chain and abilities to eliminate them allows defining the level of energy security.

Natural gas can be delivered to the country through pipelines or from an LNG terminal; besides, natural gas can be produced within the country (see Fig. 1.1).

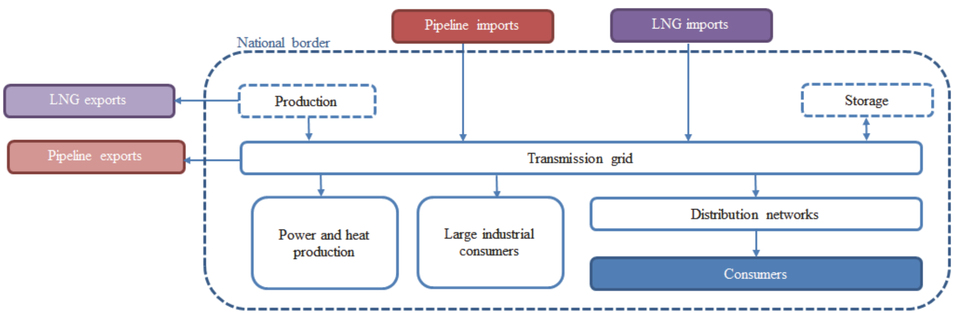


Fig. 1.1. State natural gas supply chain.[1]

Risk is an uncertain future event that can affect achievement of strategic, economic and financial objectives of an institution. This is a complex concept that includes probability of an event occurrence and estimation of the magnitude of its undesirable sequences.

[1] International Energy Agency. Energy Supply Security: The Emergency Response of IEA Countries – 2014 Edition / Internets. – http://www.iea.org/publications/freepublications/publication/ENERGYSUPPLYSECURITY2014.pdf [accessed 15 December 2015]

The view of many authors should be accepted that supply chains, including natural gas supply chains, would have to refer to possible events, which can occur accidentally, and to the fact that these events exert a significant negative impact on the system. Natural gas supply chain risk management should be the same as the circular risk analysis paradigm – **Identify > Assess and Evaluate > Mitigate > Monitor > Re-assess**.[2]

According to ISO 31000 and IEC/ISO 31010, risk management is based on risk assessment. Before making risk assessment, the context should be specified, but after risk assessment possible risk mitigating solutions are specified (see Fig. 1.2).

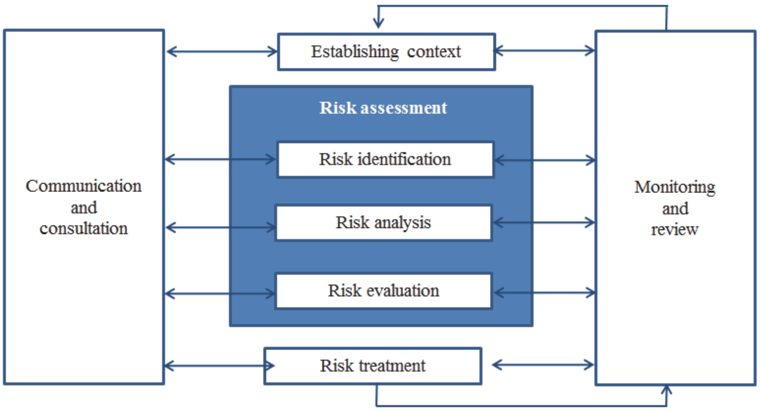


Fig. 1.2. ISO 31000 Risk management system.[3]

The context of natural gas supply chain risk management process ensures the appropriate level of the security of supply.

Despite significance of energy security, the author believes that this concept is not clearly defined. To develop the security assessment methodology of natural gas supply system, the author studies scientific literature concerning the security of energy supply concept in the context of natural gas.

1.2. Security of Energy Supply

The author's empirical study on the definition of security of energy supply has shown that "security of energy supply" has become a common term.

In the author's opinion, security of energy supply is a multidimensional value, which frames energy aspects (source security), availability aspects (supply security), as well as financial aspects (economic security).

[2] Manuj I., Mentzer J. T. Global Supply Chain Risk Management. *Journal of Business Logistic*, vol. 29, no.1, 2008, pp. 133–115.
[3] ISO 31000:2009 Risk Management – Principles and Guidelines

The Doctoral Thesis defines security of natural gas supply as "ability of national natural gas supply to satisfy natural gas demand by end use in case of natural gas supply disruptions".

As mentioned above, corresponding to ISO 31000, the context definition is associated not only with understanding of the reason of risk assessment – in the case of this Doctoral Thesis with understanding of security of energy supply and security of natural gas supply. The context definition is also associated with understanding of all the involved parties, their interrelations and responsibility, of decision making. Thus, in the author's point of view the context definition is associated with comprehension of the most appropriate management of the involved parties.

1.3. Theory of Constraints

In the analysis of management techniques, which would be applicable to security of energy supply management, the author concludes that the most precise way to do this is to use the theory of constraints as it concerns the role of constraints on activity limitation of an organisation.

The general principle of the theory of constraints is that every system (business, natural gas supply, project, organisation, etc.) has at least one constraint or "bottleneck", and elimination of this constraint produces a maximum effect in the whole system.

To solve the problem caused by the capacity constraining element and to provide the system flow balance, a logistics tool Drum-Buffer-Rope methodology (hereafter – DBR methodology) has been developed on the basis of the theory of constraints.

In terms of DBR methodology, any system constraint or bottleneck acts as a Drum, as it, by informing about its speed of operation, determines the rhythm which the rest of the system should maintain. The Rope is the method by which the system constraints can signalize to unconstrained processes, when they have to slow down, stop or accelerate. In its turn, the task of Buffer is to provide that in case of system constraints the whole system does not stop, but continue its operation.

When using the simplified DBR methodology for natural gas supply system, the Drum is considered to be natural gas market demand; natural gas storage facilities and natural gas line pack, besides, LNG supplies function as a buffer. In its turn, capacity constrained resource is considered to be a natural gas supply system element with less technical capacity.

In order to let the minimum security assessment methodology of natural gas supply system be a successful risk management tool, at the last stage of its context definition it is necessary to select such an indicator of security of natural gas supply, which corresponds to the concept of security of natural gas supply specified in the Doctoral Thesis - "national natural gas supply ability to satisfy natural gas demand by end use in case of natural gas supply disruptions", and fits within the used principles of DBR methodology. From this perspective, the author analyses indicators of security of natural gas supply further in the Thesis.

1.4. Indicators of Security of Natural Gas Supply

To assess and characterise security of natural gas supply, different indicators widely covered in academic literature are used.

Similarly to the case with the concept of security of energy supply, it should be admitted that there is a lack of a joint approach in respect to the used indicators of security of energy supply and security of natural gas supply. The authors have not reached consensus on the most appropriate indicators to characterise security of energy supply.

To characterise security of natural gas supply, such indicators are used: Gross inland energy consumption by fuel, import dependence indicator, Herfindahl-Hirschmann Index for energy import, Herfindahl-Hirschmann Index for energy balance, Shannon-Wiener Index, Risky External Energy Supply index, probability of an accident for a gas transmission pipeline of one kilometre, underground gas storage capacity, interconnection indicator, infrastructure standard N-1.

The formula of N-1 infrastructure standard characterises technical ability of natural gas infrastructure to satisfy total demand in natural gas across the calculated area in case of disruption of the largest natural gas infrastructure on the day of exceptionally high demand for natural gas demand occurring with a statistical probability of once in 20 years. To determine N-1 infrastructure standard, the formula is used (Annex 1 of Regulation No. 994/2010)[4]:

$$N-1(\%) = \frac{EP_{\max} + P_{\max} + S_{\max} + LNG_{\max} - I_{\max}}{D_{\max}} \times 100\,, N-1 \geq 100\,\%\,, \qquad (1.1.)$$

where:

EP_{max} – technical capacity of entry points (in million m^3 (hereafter – mcm) per day), other than production, LNG and storage facilities covered by P_{max}, S_{max} and LNG_{max};

P_{max} – maximal technical gas production capability (in mcm per day);

[4] Regulation (EU) No. 994/2010 of the European Parliament and of the Council of 20 October 2010 concerning measures to safeguard security of gas supply and repealing Council Directive 2004/67/EC / Internet – http://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:32010R0994&qid=1481633825022&from=LV [accessed 10 July 2016]

S_{max} – maximal technical storage deliverability (in mcm per day);

LNG_{max} – maximal technical LNG facility capacity (in mcm per day);

I_{max} – technical capacity of the largest natural gas infrastructure (mcm per day);

D_{max} – the total daily gas demand (in mcm per day) of the calculated area during a day of exceptionally high gas demand occurring with a statistical probability of once in 20 years.

When using the formula of N-1 infrastructure standard, it is possible to estimate the situation in each country.

When estimating correspondence of theconsidered security of natural gas supply indicators (diversification indicator, import risk indicator, market concentration and infrastructure indicator) to the concept of security of natural gas supply specified in the Doctoral Thesis, which is the ability of national natural gas supply to satisfy natural gas demand by end use in case of natural gas supply disruptions, as well as their correspondence to the principles of DBR methodology, the author concludes that only the principles of N-1 infrastructure standard relate to the principles of the Theory of Constraints applied in DBR methodology. In case of disruptions in operation of the largest natural gas infrastructure, consumer demand for natural gas (a Drum) defines the rhythm, which the rest of the system should maintain to ensure, and respectively the remaining natural gas supply capacity has to be sufficient (a Buffer) to cover consumer demand for natural gas (see Fig.1.3).

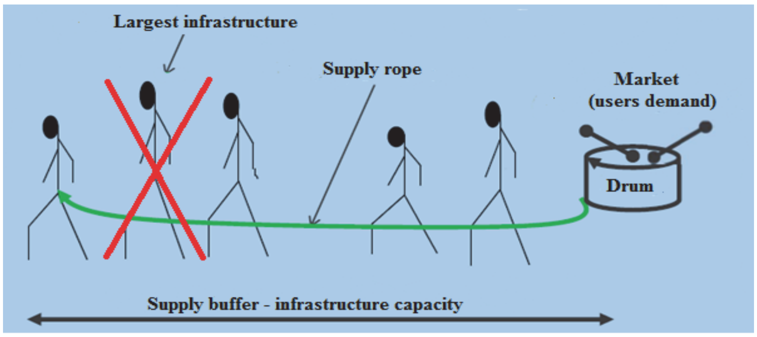


Fig. 1.3. N-1 infrastructure standard according to DBR methodology
(Source: made by the author).

As validity of the results achieved using the minimum security assessment methodology of natural gas supply system affects the resulting accuracy of N-1 infrastructure standard calculation, based on the Latvian natural gas supply system as an example, the accuracy of N-1 infrastructure standard calculation has been analysed and the necessity of its optimisation has been proven.

2. NATURAL GAS SUPPLY INFRASTRUCTURE IN LATVIA

2.1. Latvia’s Energy Mix and Trends of Natural Gas Consumption Dynamics

In Latvia for provision of national economy, commercial consumers and population with fuel, electric and heat power the imported and local energy sources are used.

In the Latvian primary energy supply, three kinds of energy resources, dominate, which have approximately equal shares – oil products (mainly gasoline and diesel) – 32 %, fuelwood – 29.9 % and natural gas – 24.4 %. The Latvian energy dependence is decreasing along with a decrease in natural gas consumption and its share in total primary energy consumption: if in 2010 it was 30.6 %, then in 2014 it was only 24.4 %.

The effect of a new natural gas infrastructure project on natural gas market can be assessed by analysing the existing Latvian natural gas supply system.

The Latvian natural gas supply infrastructure consists of transmission (main) gas pipelines, distribution gas pipelines and Inčukalns Underground Gas Storage Facility (hereafter – UGS). The characteristic feature of the Latvian natural gas supply system is that in the summer natural gas supplied from Russia is injected to Inčukalns UGS, but in the winter it is supplied to consumers from the storage facility. Thus, Latvia is the only country in the EU, which in the winter does not receive natural gas from the supplier through the pipeline. The main instrument that maintains demand elasticity is Inčukalns UGS.

2.2. Natural Gas Transmission System

Natural gas transmission system consists of gas pipeline with working pressure more than 16 bar, support facilities, items, and other inventory necessary for natural gas transmission. Latvia’s main gas pipeline network is part of the Baltic natural gas transmission system. The existing natural gas transmission system allows receiving natural gas through main gas pipelines Valdai – Pskov – Riga and Izborsk – Inčukalns UGS. In case of emergency, it is possible to supply natural gas to Latvia from Russia through Belarus and Lithuania, or through Estonia.

Latvia’s natural gas transmission pipeline network has three interconnections. Commercial measurement of natural gas on Latvian–Russian border is made at Korneti gas metering station (hereafter – GMS), on Latvian–Estonian border – Karksi GMS (Estonia), and on Latvian–Lithuanian border – Kiemenai GMS (Lithuania). Total length of natural gas transmission line is 1197 km. The analysis of pipeline diagnostic results confirms that the factor of risk of the Latvian natural gas transmission system is ageing.

2.3. Inčukalns Underground Gas Storage Facility

The total volume of natural gas in Inčukalns UGS is 4.45 billion m^3 (hereafter – bcm), including volume of active gas of 2.30 bcm. Maximum daily injection volume into Inčukalns UGS is 18 mcm and maximum storage operating pressure is 105 bar. Maximum daily withdrawal from Inčukalns UGS at the beginning of the withdrawal period (October) can reach up to 30 mcm at pressure of 105 bar, at the end of the withdrawal period (beginning of March/April) daily withdrawal decreases to 10 mcm. Similar to the Latvian natural gas transmission system, it can be concluded that for Inčukalns UGS the risk factor of the storage functioning is ageing.

2.4. Natural Gas Distribution System

Natural gas distribution system is a natural gas pipeline system with system facilities and complementary parts from a natural gas transmission system to the proprietary border, with working pressure up to 16 bar. The total length of underground gas pipelines of the Latvian natural gas distribution system is 4908 km, including PE gas pipeline – 1604 km.

Even though technological facilities of natural gas storage, transmission and distribution systems are regularly maintained, repaired and reconstructed, there is still the risk that natural gas supply to consumers is interrupted. Probability of occurrence of the mentioned risk is analysed in the following subchapter.

2.5. The Level of Security of the Latvian Natural Gas Supply System

Considering the possibility to store in Inčukalns UGS natural gas volume, which significantly exceeds the Latvian annual consumption, Latvia's level of security of natural gas supply is considered to be one of the highest in Europe.

According to the data summarized in "The Security of Natural Gas Supply in Latvia" developed in 2012 and updated in 2015 by *PSI Risks un audits* Ltd, in Latvia the probability of an accident for a gas transmission pipeline of one kilometre in length equaled 5.7×10^{-5} in 2011. This means that in the territory of Latvia an accident of gas transmission pipelines could be expected once every 15 years on the average. According to reviewed data, the accident of gas transmission pipelines in the territory of Latvia could be expected once every 16 years on the average.

The author concludes that comparing to other countries, probability of accidents of gas transmission pipelines is lower, and the probability of branch-off accidents also is not high, which proves that in general the process of natural gas supply in Latvia is sufficiently secure.

Considering the determined natural gas supply disruption probabilities, the author shares Ramboll company's conclusions on a high level of security of natural gas supply in Latvia.

2.6. N-1 Infrastructure Standard in the Baltic States and Finland

N-1 infrastructure standard determines the probability of exposure to acceptable or unacceptable risk of national natural gas supply system.

Representative selection is one of the most important conditions, providing certainty of the achieved analytic results. Taking into account that the Latvian natural gas supply system is connected to the Estonian and Lithuanian natural gas systems and, upon construction of Finnish-Estonian interconnection Balticconnector in 2020, Finland will also join the Baltic interconnected natural gas system, the author, except for assessment of the minimum level of the security of the Latvian natural gas supply system and natural gas supply system ability to compensate disruption in the largest natural gas supply infrastructure operation, evaluates national natural gas supply systems of the Baltic states and Finland, as well as specifies the minimum level of security of natural gas supply and natural gas supply system ability to compensate disruption in the largest natural gas supply infrastructure operation.

The author using formula (1.1) calculates the N-1 infrastructure standard for Latvia, which is 220.67 %, the N-1 infrastructure standard for Estonia, which is 104.48 %, the N-1 infrastructure standard for Lithuania, which is 67.88 % and the N-1 infrastructure standard for Finland, which is 93.82 %.

As N-1 infrastructure standard of Latvia and Estonia is greater than 100 %, in the event of disruption of the largest natural gas supply infrastructure the capacity of remaining infrastructure is sufficient to satisfy the total national daily demand for natural gas during a day of exceptionally high gas demand occurring with a statistical probability of once in 20 years. The author concludes that natural gas supply systems of Latvia and Estonia are exposed to an acceptable risk.

Considering that N-1 infrastructure standard for Lithuania and Finland is lower than 100 %, in the event of disruption of the largest natural gas supply infrastructure the total capacity of remaining infrastructure will not be sufficient to satisfy the total national demand for national gas during a day of exceptionally high gas demand occurring with a statistical probability of once in 20 years. The author concludes that natural gas supply systems of Lithuania and Finland are exposed to an unacceptable risk at the moment.

In order to use N-1 infrastructure standard as the criterion of the minimum acceptable risk in the minimum security assessment methodology of natural gas supply system and respectively to assure accuracy of the methodology results, the author makes verification of N-1 infrastructure standard calculation results, using response scenarios.

Based on the example of the Baltic States and Finland, the analysis of response scenarios has been performed, accuracy of N-1 infrastructure standard calculation results has been determined and the necessity to make changes to the formula of N-1 infrastructure standard calculation (1.1) or to the practices of N-1 infrastructure standard application has been proven, thus providing accuracy of minimum security assessment results of natural gas supply system.

3. THE MINIMUM SECURITY ASSESSMENT METHODOLOGY OF NATURAL GAS SUPPLY SYSTEM

3.1. Natural Gas Supply (Natural Gas Flows) Modelling in the Baltic States and Finland

The response scenarios necessary for accuracy verification of N-1 infrastructure standard calculation results are developed to define the changes in operation of natural gas supply system and in natural gas flows that should be performed by transmission system operators, to compensate in a natural gas supply system a failure in operation (disruption in operation) of the largest natural gas supply infrastructure, providing natural gas supply to all consumers in the amount demanded.

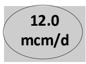
Since national natural gas supply systems in Latvia and other Baltic States are interconnected, the response scenarios assume changes in natural gas flows not only in Latvia, but also in Estonia and Lithuania, as well as in Russia and in the future in Finland.

Modelling of natural gas transmission system operation in the Baltic States and Finland is performed for an existing situation – 2015 is taken as the base year (scenario), as well as for 2020, when it is anticipated to complete such projects of natural gas infrastructure development as construction of Gas Interconnection Poland – Lithuania (hereafter – GIPL), enhancement of Latvia – Lithuania gas interconnection, upgrading Kiemenai GMS, reconstruction of Karksi GMS and construction of a new compressor station, modernisation of Inčukalns UGS, construction of Estonia – Finland interconnection Balticconnector and the regional LNG terminal.

The response scenarios are developed for the cases when there is evident maximum daily demand for natural gas.

Calculations of natural gas supply system operation in the Baltic States and Finland were performed with the help of Bentley System Incorporated software PlantFLOW designed for calculations of steady-state natural gas pipeline networks. With the help of the mentioned numerical model, natural gas flow distribution was determined in the common natural gas supply system of the Baltic States and Finland in cases of natural gas supply disruption (emergency). Natural gas transmission system operation in 2015 was taken for modelling of the operation of natural gas transmission system in an existing situation or the base scenario[5] (See Fig. 3.1).

Fig. 3.1. Existing natural gas flows in natural gas transmission systems of the Baltic States and Finland in normal conditions[6], where



– maximum daily natural gas consumption (mcm/day);

– natural gas flow, mcm/day;

– pressure, bar.

[5] Ltd. "Olimps". Analysis of interoperability of gas infrastructure projects of the Eastern-Baltic cluster proposed in relation to Projects of Common Interest list in BEMIP region and Joint Preventive Action Plan of Estonia, Latvia, Lithuania and Finland. Ltd. "Olimps", Riga, 2013. – 85 p.

[6] Ltd. "Olimps". Analysis of interoperability of gas infrastructure projects of the Eastern-Baltic cluster proposed in relation to Projects of Common Interest list in BEMIP region and Joint Preventive Action Plan of Estonia, Latvia, Lithuania and Finland. Ltd. "Olimps", Riga, 2013. – 85 p.

In case of gas flow disruption from the largest Estonian natural gas infrastructure – Karksi GMS, response scenario establishes that, considering technical limits of natural gas supply system, in the case of natural gas supply disruption through Karksi GMS, after rearrangement of natural gas flows the Estonian daily demand for natural gas will not be covered.

In case natural gas supply from Latvia's largest natural gas infrastructure – Inčukalns USG – is disrupted, natural gas supply to Latvia is organised from Russia through Korneti GMS and from Lithuania through Kiemenai GMS. Natural gas supply to Estonia is organised from Russia through Verska GMS and Narva entry point.

Considering technical limits of natural gas supply, in case of disruption in natural gas supply from Inčukalns UGS, after rearrangement of natural gas flow Latvia's and Estonia's daily demand for natural gas will not be covered – in Latvia natural gas shortage will make 6 mcm per day, and in Estonia – 2.71 mcm per day, Lithuania's demand for natural gas will be completely covered (see Fig. 3.2).

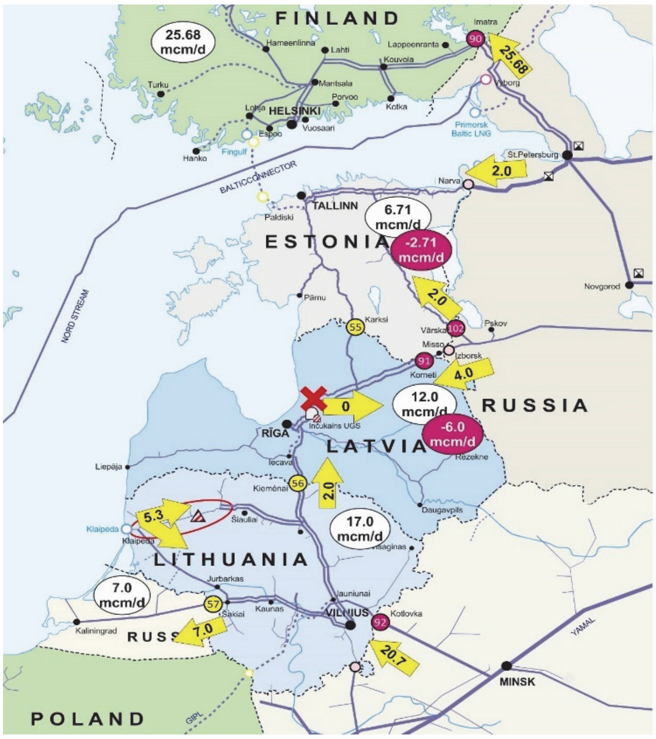


Fig. 3.2. Natural gas flows in natural transmission system of the Baltic States and Finland in case of supply disruption from Inčukalns USG (base scenario)[7], where

- uncovered demand for natural gas per day (mcm/day).

[7] Ltd. "Olimps". Analysis of interoperability of gas infrastructure projects of the Eastern-Baltic cluster proposed in relation to Projects of Common Interest list in BEMIP region and Joint Preventive Action Plan of Estonia, Latvia, Lithuania and Finland. Ltd. "Olimps", Riga, 2013. – 85 p.

Results of the developed response scenario in comparison with N-1 infrastructure standard indicate that capacity of the remaining natural gas infrastructure will not be sufficient and covered either by Latvia's demand for natural gas or that of Estonia. Having analysed the results of N-1 infrastructure standard calculation and response scenarios, the author concludes that the main difference is caused by the fact that N-1 infrastructure standard calculation does not include limiting factors of natural gas system operation.

As stated in the Doctoral Thesis, the results of Estonia's N-1 infrastructure standard calculation – 104.48 % and that of Latvia's N-1 infrastructure standard calculation – 220.67 % confirm that the remaining natural gas infrastructure is able to cover national demand for natural gas in the case of disruption in the largest natural gas infrastructure operation, being Karksi GMS in Estonia and Inčukalns UGS in Latvia. In turn, the achieved results of response scenarios in comparison with N-1 infrastructure standard indicate that capacity of the remaining natural gas infrastructure will not be sufficient to completely cover demand for natural gas.

Summarising the achieved results for N-1 infrastructure standard in the Baltic States and Finland and the response scenarios, it should be concluded that N-1 infrastructure standard produces a wrong assessment of minimum security of national natural gas supply system. The mistake is caused by formula (1.1) shortcomings associated with natural gas supply specifics and system operation affecting factors, such as actual demand for natural gas, natural gas pressure, and natural gas availability. It allows reasoning that it is necessary to integrate limits of natural gas system into the calculation formula N-1 infrastructure standard.

While improving the formula of N-1 infrastructure standard, the author suggests integrating into it limiting technical factors of natural gas system, **by replacing maximum technical capacity of natural gas supply system infrastructure with available technical capacity** during a day of exceptionally high gas demand occurring with a statistical probability of once in 20 years. The author, considering the results of modelling, suggests the following modified formula of N-1 infrastructure standard:

$$N-1(\%) = \frac{EP_a + P_a + S_a + LNG_a - I_{max}}{D_{max}} \times 100\,, N-1 \geq 100\ \%\,, \qquad (3.1.)$$

where:

EP_a – available technical capacity at entry points (exclusing recovery, LNG and storage systems, which P_a, S_a and SDG_a refer to) (mcm per day) during a day of exceptionally high gas demand occurring with a statistical probability of once in 20 years;

P_a – **available** technical production capacity (mcm per day) during a day of exceptionally high gas demand occurring with a statistical probability of once in 20 years;
S_a – **availabl**e technical storage deliverability (mcm per day) during a day of exceptionally high gas demand occurring with a statistical probability of once in 20 years;
SDG_a – **available** technical LNG facility capacity (mcm per day) during a day of exceptionally high gas demand occurring with a statistical probability of once in 20 years;
I_{max} – technical capacity of the largest gas infrastructure (mcm per day), with the highest capacity to supply the calculated area (when several gas infrastructures are connected to a common upstream or downstream gas infrastructure and cannot be separately operated, they shall be considered as one single gas infrastructure);
D_{max} – the total daily gas demand (in mcm per day) of the calculated area during a day of exceptionally high gas demand occurring with a statistical probability of once in 20 years.

Considering that the minimum security is exposed to influence of comparatively large number of factors, the author supposes that with a view to provide efficient application of the modified N-1 infrastructure formula (3.1) it is necessary to develop the minimum security assessment methodology of natural gas supply system.

3.2. Structure of the Minimum Security Assessment Methodology of Natural Gas Supply System and the Nature of Its Integral Steps

The analysis performed in terms of the Doctoral Thesis confirms that security of natural gas supply system is exposed to the influence of several interrelated factors. In turn, each individual natural gas supply system context is significantly exposed to the influence of factor action specifics. Such a situation claims of necessity to consider not only different factors affecting security, but also their interaction. The author's research proves that solving these tasks it is necessary to develop the minimum security assessment methodology of natural gas supply system.

The author suggests including the following sequential steps into the minimum security (risk) assessment methodology (see Fig. 3.3.):

1) risk identification;
2) analysis of minimum security of natural gas supply system;
3) evaluation of minimum security of natural gas supply system;
4) increasing the minimum security of natural gas supply system.

In the first step, natural gas supply operational parameters are established, which are necessary for calculation of N-1 infrastructure standard, the largest natural gas supply infrastructure and kinds of threats – limits of natural gas supply system in the event of disruption in operation of the largest natural gas infrastructure –that affect natural gas supply. When defining technical limits of natural gas supply system in the event of disruption in the largest natural gas supply infrastructure operation, the pressure in natural gas transmission system, actual storage operating pressure, as well as available flow in a certain section of natural gas transmission system should be estimated.

In the second step, the two operations are performed:

1) N-1 infrastructure standard is calculated using formula (3.1);
2) the response scenarios ae developed, which specify what kind of changes in natural gas supply system and natural gas flows should be made to compensate disruption of the largest natural gas infrastructure and to what extent supply of natural gas to consumers is ensured.

In the third step, minimum security evaluation of natural gas supply system is performed, comparing results of N-1 infrastructure standard and the response scenarios and determining what level of risk the system is exposed to. If N-1 infrastructure standard is less than 100 %, it is considered that risk is unacceptable, if it is higher or equal to 100 % – risk is acceptable.

In the fourth step, based on the level of risk acceptability, such operations are performed:

1) if N-1 infrastructure standard is less than 100 %, respectively risk is unacceptable, an action plan is developed providing that the value of infrastructure standard reaches or exceeds 100 %;
2) if N-1 infrastructure standard is equal or higher than 100%, respectively risk is acceptable, assessment of efficiency and feasibility of possible measures is made, upon which the decision is taken concerning implementation of measures.

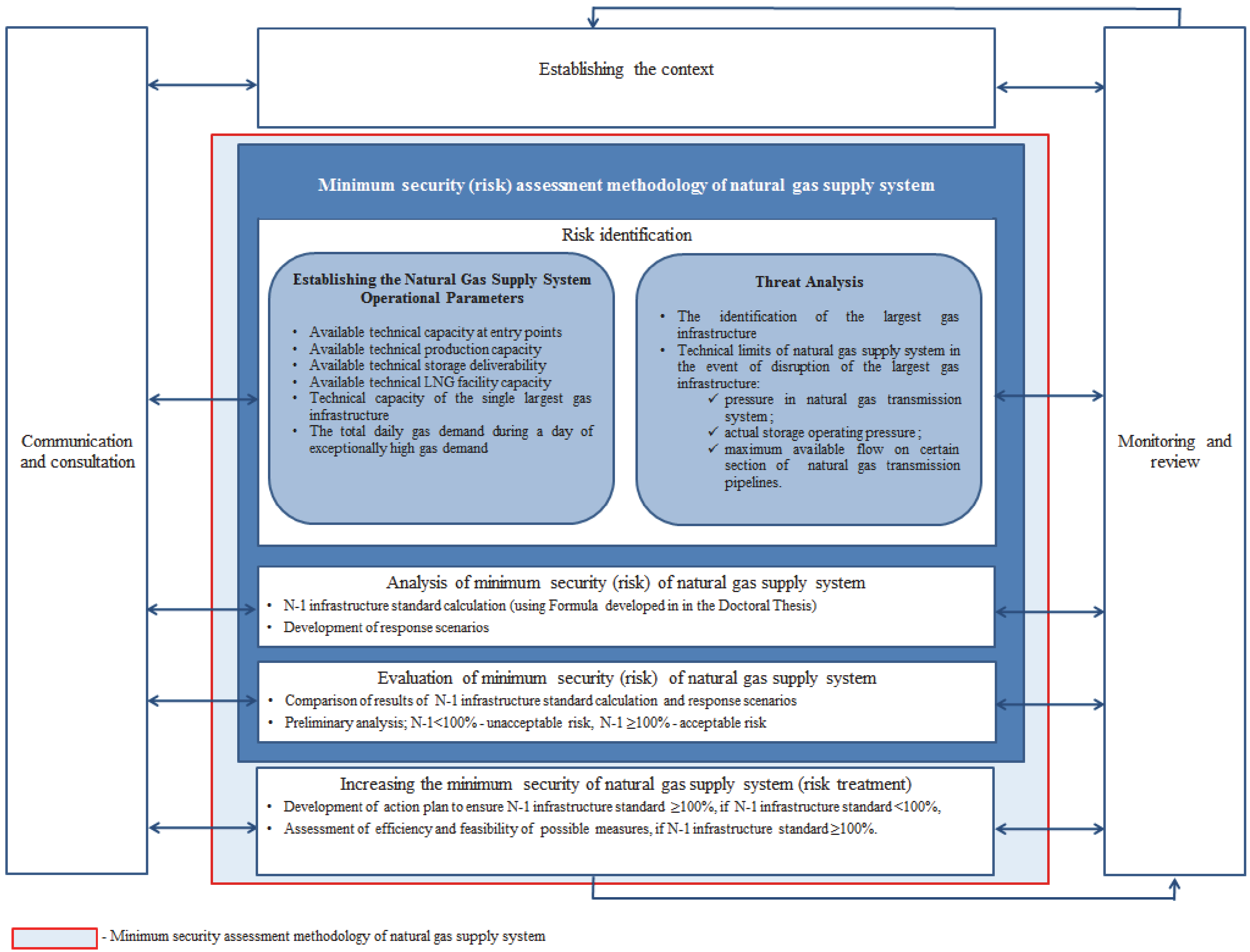


Fig. 3.3. Minimum security assessment methodology of natural gas supply system.

The author has verified and applied the minimum security assessment methodology of natural gas supply system for the development of the Latvian natural gas supply risk assessment according to requirements of Regulation No. 994/2010 approved by Decree No. 98 of the State Secretary of Ministry of Economics of the Republic of Latvia as of 23 May 2013, as well as the updated security risk assessment of Latvia's natural gas supply approved by Decree No. 184 of the State Secretary of Ministry of Economics of the Republic of Latvia as of 22 July 2015. Moreover, the minimum security assessment methodology of natural gas supply system is used for joint risk assessment of security of gas supply of Estonia, Latvia and Lithuania, which was approved by the Ministry of Energy of the Republic of Lithuania, the Ministry of Economics of the Republic of Latvia and the Ministry of Economic Affairs and Communications of the Republic of Estonia under the covenant concluded in September 2012.

The minimum security assessment methodology of natural gas supply system is easy adaptable and flexible, and it can be used in all the countries regardless of the size of their natural gas supply systems, as well as in other energy industries, for instance, power or heat supply.

CONCLUSIONS

1) Risks are possible at all stages of natural gas supply chain. Risks in natural gas supply chain are events that can cause disruption in natural gas supply (physical flow). Presence of risks causes the necessity of energy security assessment.
2) The analysis performed within the framework of the Doctoral Thesis allows concluding that there is not any joint opinion on how security of energy supply is to be understood. The author concludes that security of energy supply is a multi-dimensional value that covers energy aspects (source security), availability aspects (supply security) and physical aspects (economical security).
3) The author suggests using Eliyahu Goldratt's Theory of Constraints and DBR methodology for security of natural gas supply management, as these methodologies give an opportunity to determine, apply and eliminate constraints, which can potentially trouble natural gas supply chain operation.
4) Based on the classification of natural gas flows elaborated in the Doctoral Thesis for (emergency) cases of natural gas supply disruptions in the joint natural gas supply system of the Baltic states, the author concludes that the index of minimum security assessment of natural gas supply system N-1 infrastructure standard exposes significant shortcomings.

It does not consider technical system constraints, when providing demand for natural gas, especially the maximum demand, also it calculates unreasonably high security of natural gas supply and respectively decisions on needed investments in infrastructure are not taken to provide continuous natural gas supply to consumers.

5) To improve validity of decisions in the field of natural gas supply security management, the author suggests integrating into the existing calculation formula the constraining technical factors of natural gas operations, by replacing the maximum technical capacity of natural gas supply system-building infrastructure with available technical capacity per day with the maximum demand for natural gas, which is statistically possible once every 20 years. The updated formula of N-1 infrastructure standard is as follows:

$$N-1(\%)=\frac{EP_{\mathrm{a}}+P_{\mathrm{a}}+S_{\mathrm{a}}+LNG_{\mathrm{a}}-I_{\max}}{D_{\max}}\times 100\,,N-1\geq 100\ \%$$

6) For the minimum security assessment of natural gas supply system, the author proposes using the minimum security assessment methodology of natural gas supply elaborated within the framework of the Doctoral Thesis, consisting of four sequential steps: risk identification; minimum security assessment of natural gas supply; natural gas supply security assessment; increasing the minimum security of natural gas supply.

7) Considering the shortcomings stated in the research, the author has developed the methodology for the minimum security assessments of natural gas supply system. The methodology is flexible, easy adaptable, and it can also be used in other energy industries, for instance, power and heat supply, as well as in other countries regardless of the size of their natural gas supply systems.

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