Methane to LNG Żory Coal Mine Project

Final Report

September 2008- December 2009

Project performed in the framework of the Methane to Market (M2M) Partnership

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Project team

Project coordinating unit:

Institute for Ecology of Industrial Areas (IETU)
Katowice, Poland
www.ietu.katowice.pl

Partners :

CETUS Energetyka Gazowa sp z o.o.
Świerklany, Poland
www.cetus.pl

LNG Silesia sp. z o.o.
Rudy, Poland
www.lngsilesia.pl

Thompson Hine LLP
Washington D.C. USA
www.thompsonhine.com.

Report developed by:

Stanislaw HŁAWICZKA
Izabela RATMAN-KŁOSINSKA
Tomasz SYREK
Bogumił CHOJĘTA
Marian CENOWSKI
Ewa STRZELECKA-JASTRZĄB
Urszula ZIELONKA
Bartosz NOWAK
Katarzyna KORSZUN
Mark LUDWIKOWSKI

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Executive summary

The report presents the major outputs and key findings of the Poland Methane-to-LNG Project ("Żory" Coal Mine Project) performed from September 2008 to December 2009 in the framework of the Methane to Market Partnership (Assistance Agreement XA-83396101-0), grant solicitation RFP#EPA OAR CCD 08 01: *Activities that Advance Methane Recovery and Use as a Clean Energy Source*.
The goal of the Project was to identify and promote cost effective, near-term methane recovery and end-use opportunities in Poland. More specifically, the Project aimed at investigation of the recoverable methane resources from the abandoned Zory coal mine including: selection of the most appropriate alternative for CMM capture from the viewpoint of its potential conversion to LNG, drilling a borehole to collect CMM samples, assessing the methane obtainable resources in the abandoned mine and identifying the most promising application of the available LNG. The project attempted to perform a market analysis of LNG applications as a clean-burning fuel, together with assessing the environmental effects of the LNG application at the identified market concentrating on diesel-fueled locomotives.

The overall environmental output (i.e. the avoided methane emission from the Zory area through its capturing and utilizing as LNG) was assessed. The project proved that the methane resources in the amount of over 150 mln m^3 can be recovered from the area of the abandoned Zory coal mine. These represent a promising opportunity for extraction and conversion to LNG in a way which is technically feasible and economically viable in the near future. Investigations of the optimal way for the methane capture led to the construction of the exploratory borehole to the depth of 215 m below the ground level. The results of the test methane captures and the obtained gas parameters allow categorize the CMM as a good quality gas. The average concentration of CH_4, CO_2, O_2 and N_2 that can be considered as reference concentrations for the Zory CMM were as follows: methane – 80%, carbon dioxide – 1.8%, oxygen – 0.5% and nitrogen – 17%. The determined average concentrations of some trace components were as follows: ethane – 0.012%, propane - 0.01%, C6+ - 0.09%, hydrogen sulfide - 0.059 mg/m^3_n, organic sulfur - 0.406 mg/m^3_n, sulfur total - 0.461 mg/m^3_n, mercury - 2.0 – 18.6 ± 2.4 ng/ m^3_n. Sulfur, mercury and moisture content were much below the acceptable values for pipeline gas. The heat of combustion, Wobbe index and heating value were high enough to classify this gas as a low quality pipeline gas. Only oxygen content exceeded the acceptable limit (0.2%). These attributes indicated that the captured gas should be easy to purify and liquefy, therefore installation of LNG production may be simple, relatively cheap and economically viable to produce alternative fuel on a small scale. Trace components (especially sulfur and mercury) can be removed on small activated carbon bed.

The entire process of the Zory CMM capture, conversion to LNG (including the borehole drilling phase, gas extraction, its purification and liquefaction) and finally application at a targeted market were analyzed in detail and assessed from the viewpoint of the potential negative effects on the environment (as well as environmental benefits). The drilling of the borehole turned out to be relatively safe for the environment. Some negative effects were identified, such as pollutants emission to the air generated by the work of the diesel engine of the rig and the flushing pump, as well as at the stage of the test gas capture (flare). Some emissions to the air may also appear during gas extraction from the borehole. Noise emission was also identified as a negative environmental effect of the drilling works. However, it should be stressed that none of the identified impacts related to the borehole drilling and methane extraction was of persistent character, as they occurred only over a very limited period of time.

Potential impacts on the environment were also analyzed in the case of the CMM purification and liquefaction technologies, taking into account their applicability to process

the recoverable gas resources from the abandoned Zory coal mine. It was found that the environmental noxiousness of the methods of the CMM dehydrating depends primarily on the composition of the raw gas (e.g. the content of benzene, ethylene, toluene and xylene) and the size of the installation. That is why the final decision on the selection of the most environmentally appropriate drying method will depend primarily on the technological issues. Adsorption on molecular sieves proved the least burdensome for the environment among the considered methods of CMM dehydration. The methods of acid gas removal were assessed as posing no particular environmental risks. Since the mercury content in the CMM obtained from the Zory site was small (below 0,001 mg/Nm^3), its removal would not be necessary for CMM conversion to LNG and no negative mercury impact on the environment at the stage of CMM purification should be expected.

The results of the analysis of liquefaction methods showed that they are non-emission technologies from the viewpoint of emission to the air, water and soil (streams of generated waste). The exception is noise emission, due to the need for compressors and/or turboexpanders in the installations. This equipment may cause exceedances of permissible noise emission levels in areas where these standards are more restrictive (e.g. residential areas). Due to the fact that the Zory site is located a relatively short distance from a residential area, the environmental impact assessment report should be carried out at the design phase of the LNG installation.

In order to identify the economic and technical issues as background for potential investment opportunities, the most promising applications of LNG from the Zory borehole were analyzed together with a broad analysis of the Polish gas market. The study showed the LNG market is a niche segment of the Poland's highly monopolized gas market. Nevertheless, it represents a promising potential due to number of reasons, such as the competitive price of LNG compared to other fuels and the fact that the gas distribution network is not fully developed in Poland. The applicability of LNG as an alternative fuel in the transportation sector is also supported by favorable legal regulations, as well as a number of other industries in which LNG can successfully replace conventional energy carriers. The LNG key market players in Poland were also identified representing the following branches: ceramic industry (bricks, tiles, etc.), steel, grocery, heating, glass works, chemical industry, lime industry, asphalt plants and food producers.

The highest LNG application potential seems to be for heat and energy production, as well as for fuelling vehicles in municipal transport fleets, utility vehicles, heavy road transport and rail transport. A detailed case study performed within the project focused on examining the technical and environmental aspects and profitability of the modernization of a T448 P diesel locomotive with the aim to adapt the engine to fuelling with LNG. Results of this analysis showed that conversion of a single locomotive partially into LNG under the current market conditions is not profitable. At least 10 locomotives should be selected for conversion. The replacement of diesel oil by LNG as fuel for T448P in the most feasible dual-fuel system (60% LNG, 40% diesel) allows achieving an environmental effect in the form of avoided emission of 7.6 Mg of carbon dioxide, 0.7 Mg of nitrogen oxides, 0.1 Mg of particulate matter PM10 and 0.05 Mg of sulfur dioxide. In the case when a larger number of locomotives are modernized, the environmental effects will multiply respectively.

From the technical and environmental viewpoint, LNG can successfully replace conventional fuels (in particular hard coal used in small and medium municipal installations). Therefore, serving as a complimentary set of data on environmental implications, a study devoted to CMM to LNG application for energy production purposes in a municipal heating boiler installation was carried out. This application was considered from the viewpoint of the significant environmental outputs it may generate. It represents high potential, particularly in areas under special protection due to natural qualities, nature conservation (e.g. national parks) or health resorts. Analysis of the environmental effects of replacing hard coal by LNG in a medium municipal heating boiler installation proved the benefits of methane application as energy carrier. When combusted, LNG does not generate any dust or solid waste. Moreover, compared to hard coal, the use of LNG fuel allows elimination of nearly all emission of SO_2, heavy metals, aromatic hydrocarbons and also reduces the emissions of NO_2 by 67% and CO and NMVOC emissions by 91,5%.

It was assessed that CMM captured from the abandoned Zory coal mine will help avoiding ca 490,000 m^3CH_4 emitted per year (351 Mg CH_4/year), which recalculated to CO_2 emission, is an equivalent of 7.371 Mg of CO_2 emitted yearly. This effect can be leveraged by the application of LNG as a clean, alternative fuel.

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1. Introduction

This report presents the major outputs and key findings of the Poland Methane-to-LNG Project (Żory Coal Mine Project) performed from September to 2008-December 2009 under the Methane to Market Partnership (Assistance Agreement XA-83396101-0), grant solicitation RFP#EPA OAR CCD 08 01: *Activities that Advance Methane Recovery and Use as a Clean Energy Source*.

1.1. Background

Today there is an ever-pressing need for clean renewable and alternative sources of energy. Poland, like much of Europe, is becoming increasingly dependent on imported hydrocarbons as domestic fossil fuel resources decrease. Furthermore, the European Union's strategic objectives, related to the Climate and Energy Package, pose a challenge to limit emissions from Poland's energy sector. In light of these factors, diversification of natural gas and oil supplies becomes an even more important goal.

Methane is a clean-burning energy source that is already utilized across the world in its gaseous form as "natural gas." Compared to carbon dioxide, methane greenhouse potential is 21 times higher. This means that a reduction of methane emission by one tone is an equivalent to 21 tones of avoided CO_2 emission. Considering the CO_2 amount generated as a product of a combustion reaction, an effective reduction of methane emission recalculated into CO_2 amounts 18.25 tons of CO_2 per one tone of CH_4.

Traditionally, methane is extracted from methane deposits trapped hundreds of meters below the surface of the earth. However, methane is present in many waste gas sources, including coal mine methane (CMM) and coal-bed methane (CBM). These waste gas sources of methane are often comprised of a number of other contaminants that must be removed before the methane can be used. By implementing advanced technology, CMM/CBM can be purified and liquefied economically on a small scale. The resulting liquefied natural gas (LNG) is a clean-burning alternative fuel that can be utilized in a number of industries, including transportation.

LNG is a superior fuel due to its higher energy content, which makes it easier to transport and store than natural gas. LNG can be transported economically in tankers over long distances to end users; however, small distributed-scale production can be used to place LNG plants in close proximity to end users, thereby eliminating the need to transport this fuel over long distances.

Coal **M**ine **M**ethane (CMM) emissions are one of the major sources of anthropogenic methane emissions in Poland. The top 20 percent of underground mines account for approximately 90 percent of CMM emissions, and coal mining in Poland is the source of 21 percent of the country's overall methane emissions [1]. CMM resources in Poland have been assessed many times in recent years. Depending on the source of data, they range from 355 [2] to 1328 billion m^3[1]. The potentially obtainable CMM in Poland recalculated into pure methane amounts 45 290 billion m^3 in that 24 495 billion m^3 originating from areas where coal extraction activities are carried out [3]. As of 1997, about 300 million cubic meters of methane were collected from active Polish coal mines annually. Most of the collected methane (65-70 %) was used onsite at the mines for heat, power, or coal drying. Some of the methane was sold to outside consumers for use in oil refineries, chemical plants, and steel mills.

However, methane resources from abandoned coal mines have been largely ignored. Currently, it is more difficult to determine the methane emissions from abandoned coal mines than to calculate them in active coal mines. In active coal mines, methane collection is constantly monitored and calculated. Quantitative (flow of coal mine gas and ventilation air) and qualitative (content of methane in coal mine gas and ventilation air) measurements are performed. The data thus obtained is analyzed and recorded. In abandoned coal mines, by contrast, no measurement or monitoring of methane is being performed, so methane emissions cannot be assessed.

The release of CMM from broken rock mass in an abandoned coal mine occurs continuously over time. This release can continue even several decades after the mine has been abandoned, due to a natural rise in pressure and water levels. The CMM thus released may then migrate from the mine in an uncontrolled manner. The migration of CMM may occur through shafts that have not been fully sealed or through rock mass into the ground. Methane migration is a serious environmental and safety hazard. Methane migration through abandoned workings into neighboring active coal mines poses an additional threat by creating the danger of explosion in work areas, making it necessary to increase mine ventilation with attendant costs.

The Zory Coal Mine Project differs from "classic" projects typically involving methane conversion into electricity or heat using engines, or into pipeline quality gas as it attempted to introduce distributed-scale purification and liquefaction technology in Poland as a viable option for efficiently converting fugitive methane gas into LNG.

1.2. Project team

The project was executed by a team coordinated by the Institute for Ecology of Industrial Areas (IETU) in Katowice, Poland and the following contractors: LNG Silesia, sp z o.o., CETUS-Energetyka Gazowa sp. z o.o, and Thompson Hine LLP, Washington, D.C.

IETU is an R&D unit acting under the Polish Ministry of Environment. IETU was responsible for the overall project coordination. Because of its experience, qualified personnel, and research background, IETU conducted all of the Żory Coal Mine Project's environmental impact analyses, including the assessment of the mitigation of methane emission and the influence on the environment of the targeted LNG application, environmental analyses of the LNG technologies and technologies for purification of CMM at a potential liquefaction plant in Zory, as well as the assessment of the methane capture phase (including the borehole drilling phase). Part of gas sample analysis were also carried out at IETU.

CETUS's business activities focus on comprehensive services related to such industries as oil and gas pipeline systems, municipal water supply and sewage systems and heat supply networks. The company is the exclusive owner of a license issued by the Ministry of Environment for searching and developing coal mine methane within the abandoned Żory coal mine area. CETUS was responsible for all geological works included in the Żory Project. These works included developing the estimate of obtainable methane resources, evaluating the state of existing research and technical wells, preparing the plan of geological works, supervising the borehole drilling activities obtaining all the necessary permits and agreements, performing the gas tests and analysis of the gas samples.

LNG Silesia specializes in the design, implementation, and operation of small distributed-scale liquefaction systems. LNG Silesia's experience contributed to the technology assessment to determine the appropriate design of the purification and liquefaction facilities, the assessment of the LNG market in Poland and the development of the Case Study on the application of LNG as a locomotive fuel.

THOMPSON HINE - established in 1911, is a full service law firm and today is among the largest corporate law firms in the United States. The firm's experience ranges across the broader energy sector, including involvement in fuel, transmission, and power generation projects in both developed and developing countries. Coordinated specialized teams within the firm address the implementation of domestic and international GHG emissions reduction projects. The firm's approach combines lawyers in the environmental, energy, regulation, project finance, major projects development, securities and commodities regulation, and international trade practices.

1.3. Project Area

Figure.1. Location of the project area

The project was carried out in the area of the abandoned Żory coal mine, in the southwestern portion of the Polish part of the Upper Silesia Region, approximately 10 km southeast of the city of Rybnik, close to the boarder with the Czech Republic (Fig. 1).

Administratively, the project area belongs to the Silesian Voievodeship. The region of the Upper Silesia is the country's most highly industrialized area and one of the most heavily industrialized regions in Europe. Until recently, it was inextricably linked with heavy industry and, while this continues to dominate (60 mines, 18 iron and steel foundries), other sectors are rapidly developing(in particular the automotive industry). The region is also covered by the country's densest network of express roads. Upper Silesia is perceived as a region that is highly attractive for foreign capital investments and with little risk. Over the last seven years, foreign companies have invested approx. 14 billion USD here. In terms of foreign trade, the region is in second place in the country and has recorded the nation's highest positive trade surplus.

The Zory area is very diverse, which affects site development planning. The town of Zory has dense building development and is located in the western part of the area. The remaining area has dense building development located near the main roads.

Coal production in the Żory mine began in 1979 and was discontinued in 1996, with formal abandonment of the mine occurring in September 1997. The abandonment of this mine consisted of filling the two working shafts and embanking the main heading at the active levels of the mine. The Żory coal mine extracted coal from 12 beds at the levels of: 400, 580, 705 and 830 meters b.g.l. After the mine liquidation process was completed, substantial amounts of methane produced from desorption of hard coal beds of high methane bearing capacity and affected by mining, accumulated in unflooded parts of the goafs.

The Żory coal mine was a methane bearing mine, and its absolute methane bearing capacity (i.e. the total amount of methane liberated from the mine) was in the range of

46,3 m^{3}CH$_4$/min in 1987 to 17,1 - 18,7 m^{3}CH$_4$ per minute in the final stage of the operation (1995 - 1996). The mine used a demethaning system, which captured from 2,9 to 11,5 m3 per minute . During the entire period of the mining activity (1979 – 1996) the mine's demethaning system captured more than 51 MM m^3 CH$_4$ altogether.

2. Project goal and objectives

The overall goal of the Zory Coal Mine Project was to identify and promote cost effective, near-term methane recovery and end-use opportunities in Poland. More specifically, the project aimed at investigation of the recoverable methane resources from the Zory coal mine, including selection of the most appropriate alternative for CMM capture from the viewpoint of its potential conversion to LNG, assessment of the obtainable resources and identification of the most promising application of the available LNG. This analysis was carried out, taking into account economic and environmental issues as a background for investment opportunities.

The project attempted also at performing a market analysis of LNG applications as a clean-burning fuel, together with assessing the environmental effects of the LNG application at the identified targeted market. Since LNG as a fuel for vehicles seemed to be the most promising application, the study of the target market focused on diesel-fueled locomotives. One of the project objectives was to perform a Case Study of the targeted market (i.e. a local railway company with a potential to convert their diesel fueled locomotives into LNG).

Beside investigating the technical and commercial aspects of CMM recovery and LNG production, the project was aimed at determinating the environmental impacts accompanying different phases of these processes, including the phase of methane capture, gas purification, liquefaction and the final use as LNG fuel. An attempt was made to assess the overall environmental output (i.e. the avoided methane emission from the Zory area through its capturing and utilizing as LNG).

The Żory Coal Mine Project contributes to the reduction of methane emission in Poland and promotes a cost effective, near - term solution for production and application of a clean-burning alternative fuel resource – LNG. Additionally, methane collection from the Żory area substantially reduces methane migration into the neighboring, operating mines. In this aspect the project may also contribute to an improvement in industrial safety.

3. Experimental

The key success criteria for the Zory coal mine project assumed that the worked out solutions must be feasible, cost effective and realistic in a relatively short time perspective. Therefore, the experimental part of the effort concentrated mainly on the identification and testing of the most appropriate methane capture method from the viewpoint of its conversion to LNG. Initially, three alternatives were considered: use some of the existing 43 wells, drilling a new borehole or use of the existing underground infrastructure of the operating coal mines adjacent to the Zory coal mine area. Out of them, drilling of a new borehole turned out the most reliable option ensuring a successful performance of a series of gas capture tests. An experimental borehole was drilled to the depth of 209 b.g.l., according to a tailored Plan of the Drilling Works. Five gas capture campaigns were performed in the period of 24 June – 7 July 2009, based on a dedicated Test Plan. These tests provided key data on the parameters of the CMM from the Zory coal mine, which served as a starting point for both balancing the obtainable methane resources at the site and assessing the liquefaction technology implementation and its commercial and environmental implications. This section presents in detail the scope of the performed activities, together with the summary of the obtained results.

3.1. Project site

As described in the introductory section, the abandoned Zory coal mine area is a relatively vast piece of land, covering the surface of 16,7 km^2.

Despite its large dimensions, the project site has been relatively well-recognized due to several available geological reports as well as data concerning assessment of the deposits

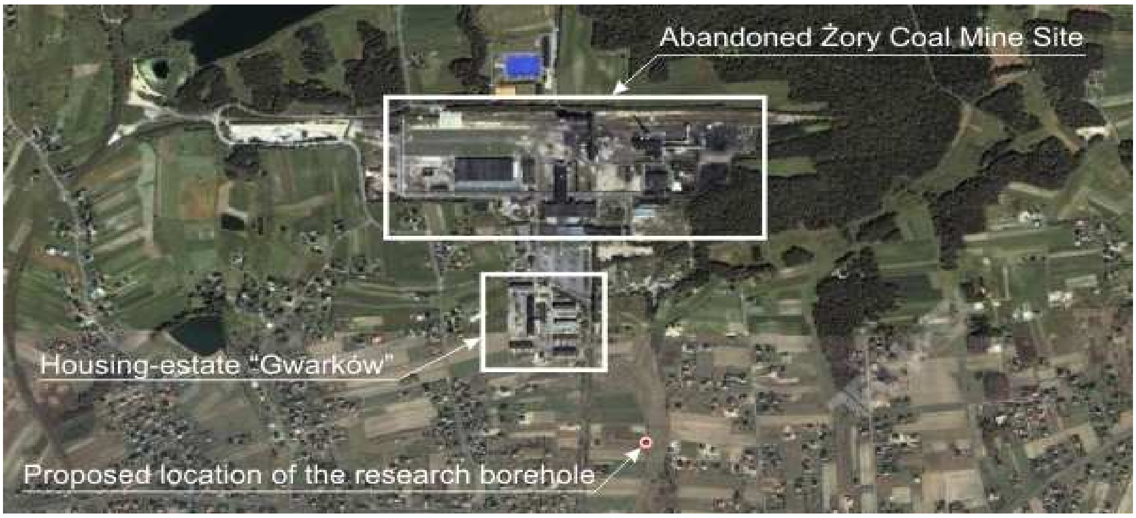

Figure 2. Location of the project site

and the methane bearing capacity performed during the operation of the mine. The location of the research borehole was determined first of all by geological conditions, location of the galleries in the abandoned Zory mine and the availability of space on the surface above the mine to mount a drilling rig. The selected drilling location (Fig.2) is situated in a relatively short distance of ca. 600 m from a closed down central Zory mine shaft.

Also, there were a number of exploratory boreholes made during the 1950s – 1970's. Data from all these sources provided a good recognition of the site conditions, including its geological and hydrological profile as well as obtainable deposits within the project site.

Site geology

The geological structure of the project site is composed of Quaternary, Tertiary and Carbon formations. The Quaternary formations occur directly on the surface and cover the entire project site. Their thickness oscillates from 1-111m. The Quaternary deposits are composed mainly of clays, sands, loess and gravels. They are underlined by Tertiary formations, which at the same time overburden the Carbon formations with complex deposits . Within the project site, the thickness of these deposits increases from 20 m to 413m southwards. From the lithological viewpoint, Tertiary deposits are composed of silts transforming into siltstones in deeper strata. There are some insertions of marl formations observed. The Carbon formations are represented by productive carboniferous deposits occurring to the depth of 1200m. They are represented by Orzesze beds (seams 300) and Rudy beds (seams 400). The Orzesze beds extend directly under a several hundred meters thick Tertiary formations. Their roof forms at the same time the top of the carboniferous deposits and therefore their thickness depends on the configuration of the Carbon formation's surface and the tectonic structure of the area. The Rudy beds extend over the entire project site and overlay the anticline (Saddle) series. Seam 401 constitutes the roof of the Rudy beds.

The lithological profile is dominated by siltstones and mudstones (accounting for 60-80%) over sandstones and numerous hard coal insertions. The hard coal beds often transform into coal shale and occur most frequently in the coaled siltstones formations.

Two zones of methane occurrence can be distinguished within the project site:

- zone of free methane (coal mine methane – CMM), accumulated in abandoned workings on the level of 400 and 580 m below ground level at the Żory coal mine and in porous sand stones occurring in the roof sections of carbon formations,

- zone of methane adsorbed into the solid matrix of the coal (coal bed methane – CBM) located in the non-extracted sections of the coal bed, generally below 600 under the ground level, locally even below 1000m .

Site hydrology

There are three water-bearing horizons within the site: Quaternary, Tertiary and Carboniferous. The main Quaternary aquifer is deposited within the thill of the Quaternary formations. The aquifer is mainly built of sands, gravels and singular rock boulders. It is hydraulically connected with the surface water bodies, aquifer horizons in the river valleys and accumulation terraces of the overlaying Holocene formations. The Quaternary aquifer is supplied by a direct infiltration of atmospheric precipitation. A thick layer of impermeable, Tertiary clay deposits separates the Quaternary water bearing horizon from the carboniferous aquifer. The Tertiary aquifer is connected with permeable deposits (sands, sandstones and conglomerates) present between the typically impermeable silt formations. The carboniferous aquifer underlies the Tertiary silts, silt stones, sands and sandstone layers nearly all over the site. The silt deposits constitute an insulation layer for the carbon aquifer, separating it from the impact of the overlaying quaternary and tertiary formations. The aquifer is built of sandstones of the Orzesze and Rudy layers and extends to a depth of 90 – 1500m below the ground level. There is no direct infiltration of waters from the project site to the carboniferous aquifer. The water originates from the static resources of the Carbon deposits, supplied by infiltration from areas outside the project site.

As for surface waters, there is a drainage trench running in the vicinity of the drilling site. It collects and transports water from the fields. The nearest large water reservoir is the Papielok pond, located a distance of about 1 km in the north-western direction from the drilling site.

Nature conservation and protected areas

The nearest legally protected area is the Landscape Park „Cysterskie Kompozycje Krajobrazowe Rud Wielkich”, the border of which is located a distance of 5 km in the north-eastern direction from the project site.

Other places of nature conservation are located in a further distance from the site include a bison reserve „Żubrowisko” in Pszczyna (20 km eastward from the drilling site) and a special birds protection site Natura 2000 „Upper Vistula Valley” (20 km in the southeastern direction from the drilling site).

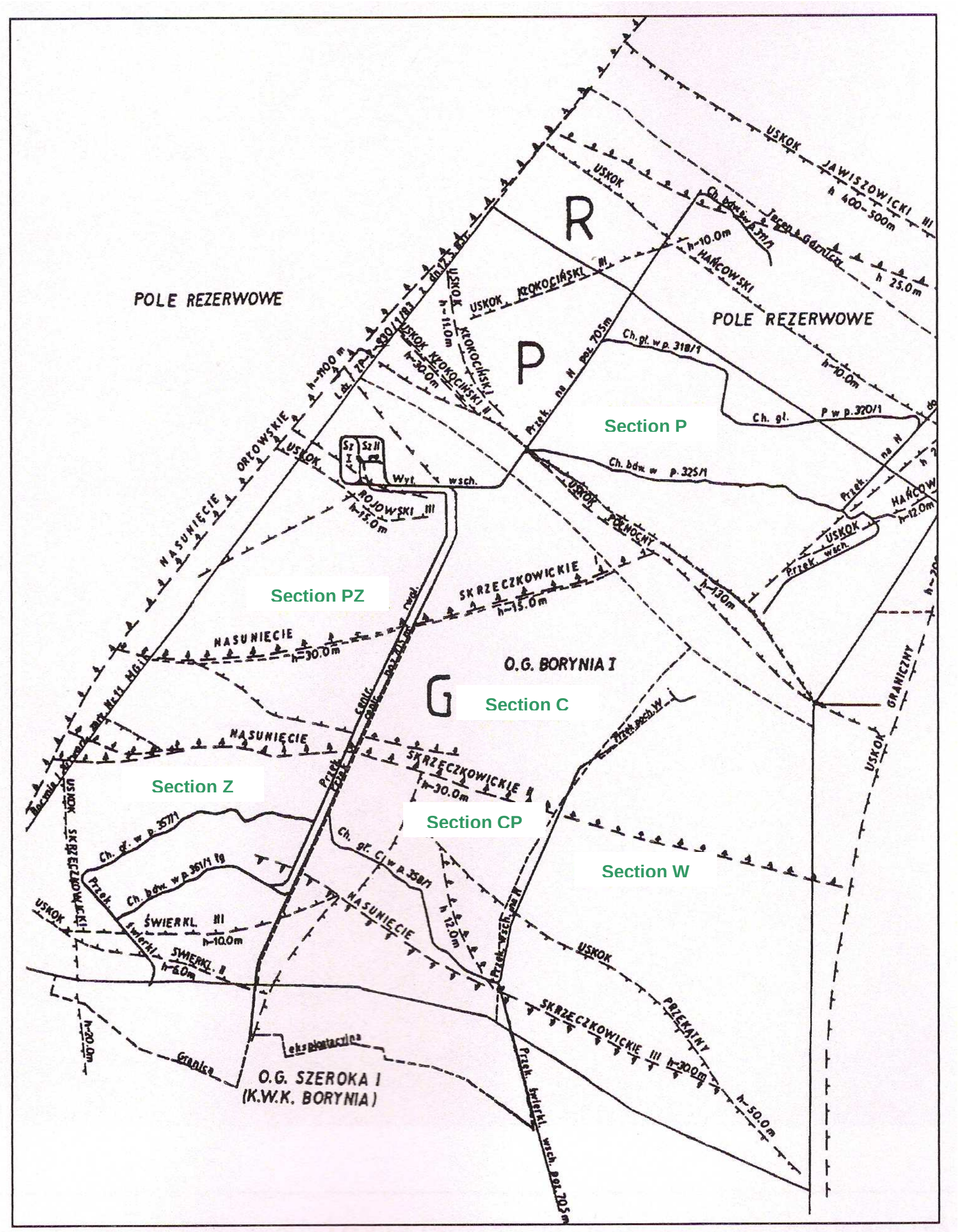

Figure 3. Map of the project area including geological dislocations and division into sections

The entire Żory area has been divided into several sections „Z", „W", „PZ", „C", „P" taking into account the geological conditions and the tectonic structure, as well as dislocations (both: meridional and parallel, Fig. 3). These sections have been also characterized for the methane bearing capacity of the coal beds. In section „PZ", above 400m level, the upper methane zone of the deposit has been identified. The roof of a deep methane zone occurs below the level of 580m. Average values of the methane bearing capacity at all levels significantly exceed the value of 2,5 m^3 CH_4/Mg csw (standard cubic meter of methane per metric ton of pure hard coal). In section „P", the results of the methane bearing tests show that the methane zone occurs at all levels. However, the average values for each level are below 2,5 m^3 CH_4/Mg csw. In sections „Z" „C and P", the mining activities were conducted only on the levels of 580m and 705m. Methane zone embraces these levels and the average values exceed 2,5 m^3 CH_4/Mg csw in section „C" and section "Z" on the level of 705m.

From the South, the Żory mining area neighbors with the operating Borynia coal mine, while from the West a diagnostic cross-cut at the level of 400m connects the abandoned Zory coal mine with the operating Jankowice coal mine.

3.2. Methane capture from the Zory site

3.2.1. Selecting the methane capture method

One of the key objectives of the project was to assess the obtainable methane resources in the Żory area from the viewpoint of its capture for LNG purposes. Detailed knowledge about gas characteristics, especially methane and oxygen content, is extremely important, because CMM conversion to LNG is economically and technically viable only if methane content exceeds a certain value. Therefore, the first phase of the project aimed at identifying the most suitable option to capture and assess the obtainable methane deposits, with the purpose of their potential commercial excavation and usage. The following key selection criteria were set up:

- **feasibility:** the solution must be feasible in terms of time, resources, required geological, legal documentation and licenses,
- **accessibility of methane resources**: the solution must ensure the most convenient access to the obtainable methane resources,
- **reliability**: the selected option must ensure a continuous, high-volume supply of gas flow from deposits of high methane bearing capacity

In addition, each criterion was supported by a detailed analysis of the historical data and geological documentation concerning the activity of the Zory coal mine, the adjacent operating mines, as well as the project site.

When planning the methane capture method, the following three options were considered and analyzed:

Option 1 - Use some of the historical boreholes existing within the investigated site

Analysis of the obtained historical documentation showed that there were 43 exploratory boreholes made within the project area in the period of mid 1950s and late 1970s. They were made for different purposes by different companies. According to the data, the depth of the boreholes ranged from 207 –1629m b.g.l. The option assumed investigation of the location with respect to the accessibility of methane resources and technical condition of the existing boreholes, as well as their potential renovation to enable methane capture.

The most important criteria used for the analysis of the historical boreholes from the viewpoint of their applicability for methane capture included:

1. Location of the existing research boreholes with reference to the carboniferous roof and the most convenient access to the methane deposit in its highest possible point.
2. Parameters of the existing research boreholes including purpose of the drilling, diameters, depth of the piping, sealing/closing, water-bearing strata, lithographic and stratigraphic profile, depth of the sole, thickness of the geological layers, method of drilling and borehole liquidation.
3. Data from the methane bearing capacity measurements .
4. Location against the mined coal beds, cross-cuts and inclined drifts.

The historical boreholes are located over a relatively vast area of the Żory, with only 27 boreholes located within the investigated site (Figure 4). The location criterion allowed to narrow down the study to the 27 wells.

A further detailed analysis of the historical data combined with site visits showed that most of the boreholes were suppressed under the ground level and their technical condition was rather poor. Out of 27, only three historical boreholes were identified as representing some potential for methane capture: Zory 30 (Figure 5), Żory 31 (Figure 6) and Zory 20 due to their location close to the deposit. These boreholes were examined for their technical condition in view of potential renovation.

Examination of the technical condition of wells 30 and 31 and the negative results from the tests made using a methane detector showed that these boreholes could not be used for project purposes.

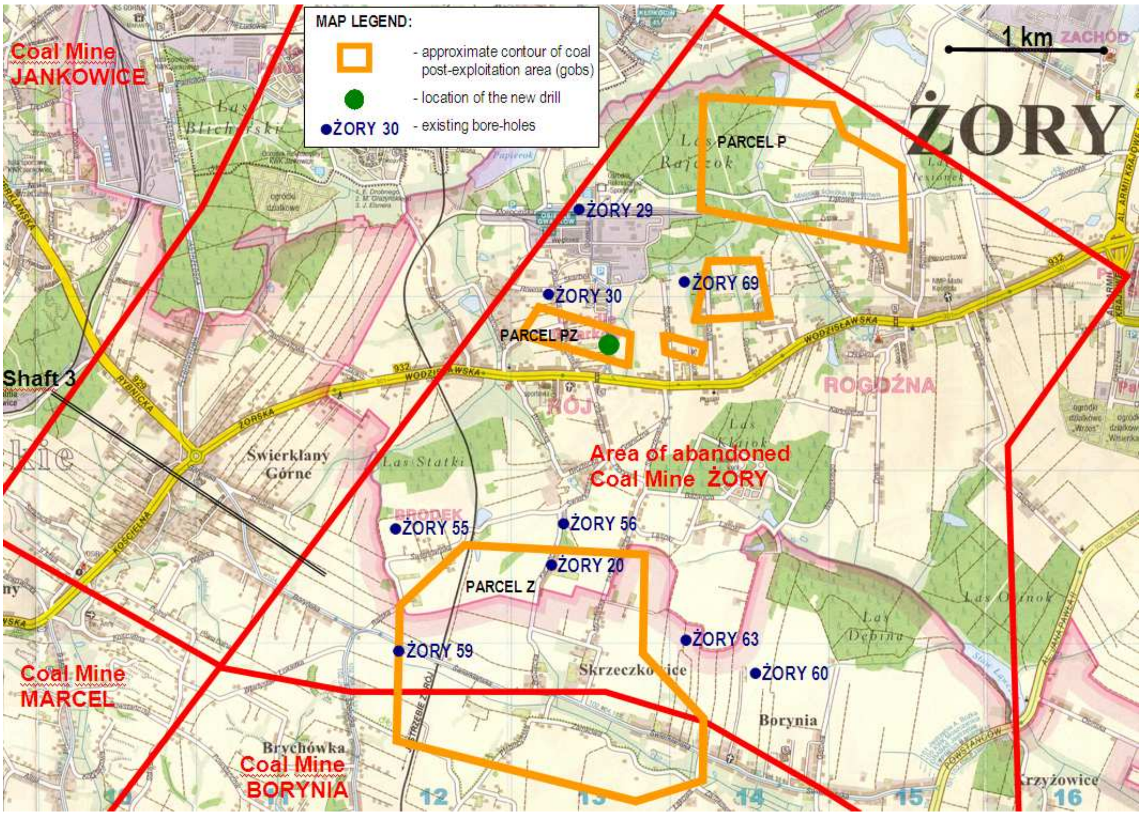

Figure 4. Location of the selected boreholes and approximate contours of post-exploitation area

Figure 5. Borehole Żory 30

Figure 6. Borehole Żory 31

The only borehole which was identified to meet the requirements of the proper location and depth of the borehole-tubes was Żory 20. As the next step, an analysis was made concerning the potential of renovating the Żory 20 borehole. Based on a detailed study of the coal beds maps and the Żory 20 borehole documentation, the following data were established:

- the highest coal beds in the area of the borehole are located at the depth of 580 m;
- the borehole is placed above the central cross-cut situated 705 m below the ground level;
- the carboniferous roof is located at the depth of 316m;
- the borehole Żory 20 has been sealed with cement in sections: 0÷10m and 142÷1006 m. The section between 10÷142m deep has been flooded with a thick liquid flush.

Based on the above data a simple SWOT (Strengths, Weaknesses, Opportunities, Threats) analysis was made concerning the renovation of the Żory 20 borehole.

SWOT analysis of the renovation of the Żory 20 borehole.

Strong points	***Weak points***
✚ borehole pipes reaching below the carboniferous roof ✚ located in Section Z characterized with high methane capacity of the coal beds; ✚ a section of 132m flooded with a thick liquid flush, which should facilitate the reconstruction (broaching)	- borehole location – it covers the safety pillar for the central cross-cut – the borehole is not placed directly above the abandoned working but only within the influence area; - age -52 years – technical condition of the pipes (corrosion) can preclude the reconstruction and mining; - there are thick deposits of argillaceous formations in the carboniferous roof which insulate the coal beds. These rocks have a very low strength, especially the mudstones occurring directly to the coal bed. They cause the sealing of slits inhibiting methane migration; - no drilling company decided to estimate the costs of the borehole renovation. Only an „open book" order was possible with the chances to succeed estimated for 50/50.

In view of the majority of negative aspects and a high risk of the failure, as well as due to the lack of the renovation cost assessment, alternative 1 was eliminated from further studies.

Option 2 - Drilling of a new exploratory borehole

This option assumed construction of a new exploratory borehole in a selected optimal location based on a detailed analysis of the available data on the methane bearing capacity, the geological structure of the area and the existing underground infrastructures. Both the location and the parameters of the borehole should ensure meeting project objectives .

A detailed study of available documentation was made to determine the optimal location of such borehole. The analysis of the methane bearing capacity tests made in the years 1985 - 1996 in the underground excavations of the abandoned Żory coal mine led to the conclusion that the best conditions for methane accumulation in the coal beds were in Section „PZ" (Figure 3), where high values of the methane bearing capacity had been identified at the levels of 400m and 705m. It was also found that drilling within this Section ensured the most convenient access to the methane deposit in the existing gobs located in the highest point of the Żory coal bed (215 m below the ground level). The identified location of the borehole was also advantageous due to a very easy methane migration to the perforated section of the borehole through the pores and cracks in the sandstone overlaying the first mined deposit. The presence of the abandoned workings in several beds extracted one after another were an additional advantage for the location.

The exact location of the borehole was determined at a site which, according to the spatial management plan has neither farming nor construction land use functions. The nearest inhabited buildings are located a distance of over 100m and the nearest housing estate “Gwarkow” is located about 500m (Figure 2). The location and the functions of the adjacent areas had an essential meaning as the drilling works could be strenuous for the surroundings due to noise and heavy equipment used.

In view of all the positive aspects and a relatively low risk of failure, option 2 seemed to be meet all the criteria set up for the selection of the optimal methane capture method from the Zory coal mine deposits. The construction of the borehole and the methane capture tests have been described in more details in the following sections of the report.

Option 3 - Use the existing underground infrastructure

This option assumed the use of the existing underground infrastructure of the neighboring active coal mines for methane capture. Methane from the Zory area migrates via headings and cross-cuts to the neighboring active mines: Borynia and Jankowice. There is a diagnostic cross-cut at the level of 400m which connects the abandoned Zory mine with the operating Jankowice coal mine.

Based on the available data it has been found that the methane captured from the diagnostic cross-cut at the Jankowice coal mine is transported to the cumulative collector and further to the demethaning station at this mine . Despite that fact, there is a continuous quite intensive uncontrolled methane liberation through the broken rock mass into the shaft at the Jankowice coal mine. Capturing this gas would require construction of an independent pipeline in the shaft facilitated with a compressor. Such construction would require obtaining a number of permits and licenses necessary to construct the capture system and operate it within an active area of the Jankowice mine. A detailed analysis of all advantages and disadvantages of the considered methane capture option showed that it did not meet the assumed criteria of feasibility, reliability and accessibility due to the following reasons::

- capturing methane using the Jankowice coal mine infrastructure at the initial exploratory stage turned out too complicated from the formal and legal point of view;
- the cross-cut was gradually flooded and there was a risk of its complete flooding;
- the age of the pipeline transporting methane in the cross-cut - over 30 years old, it was impossible to determine its technical condition and usability for methane capturing;
- it was difficult to determine whether the methane captured at the Jankowice coal mine originates from the abandoned Żory coal mine area. Proving the origin of the gas would only be possible with the use of a gas marker method however this would require either renovation of an existing borehole and/or drilling a new one within the Żory area;
- the necessary costs were far beyond the available budget of the project and there was a high risk that the obtained data could be unsatisfactory due to the above mentioned threats.

Among the considered methane capture options, only option 2 i.e. construction of a new borehole met the success criteria set up for the selection and was burdened with the lowest risk of failure.

3.2.2. Determining the location of the exploratory borehole

Determination of the exact, optimal location for drilling a new exploratory borehole required a detailed study of the geological data, location of the underground infrastructures, measurement data from the methane bearing capacity tests, etc. It was stated that the abandoned working of the Zory coal mine together with a network of fractures (cleats) and fissures of the rock mass created a free methane collector reaching the depth of about 705m below the ground level i.e. the level of the mine waters table which leak to the workings of the neighboring Borynia coal mine. The capacity of that collector has been initially estimated for several dozens of million of cubic meters. The collected gas originated from the lower strata of the carboniferous roof, some of it was released from the methane saturated waters. During methane capturing, the collector will be constantly refilled with methane propagating from the non-exploited coal beds.

The analysis of the methane bearing capacity tests made in the years 1985 - 1996 in the underground excavations of the abandoned coal mine Żory led to the conclusion that the best conditions for methane accumulation in the coal beds were in Section „PZ" where high values of the methane bearing capacity had been identified at the levels of 400m and 705m, as well as high average values of methane bearing between the carboniferous roof and the depth of 705 m.

In Section “PZ” the most convenient access to the methane deposit is in the gobs of the 327/1-2 coal deposits. The gobs are located in the highest point of the Żory coal bed (215 m below the ground level) with reference to the ground surface being thus relatively accessible for drilling. The location of the experimental borehole in Section ”PZ" was also advantageous due to a very easy methane propagation to the perforated section of the borehole through the pores and cracks in the sandstone overlaying the first mined deposit 327/1-2. Methane liberation and migration was additionally facilitated by the impact of the former mining operations as many of the abandoned workings within the vicinity of the planned borehole location run through several seams extracted one after another.   .

The final location of the experimental borehole was determined within the Section „PZ", above the interpenetrating gobs of 327/1-2 and 327/4 coal deposits, in a point where the drilling depth would be the shallowest to ensure access to the methane deposits (Figure 7)

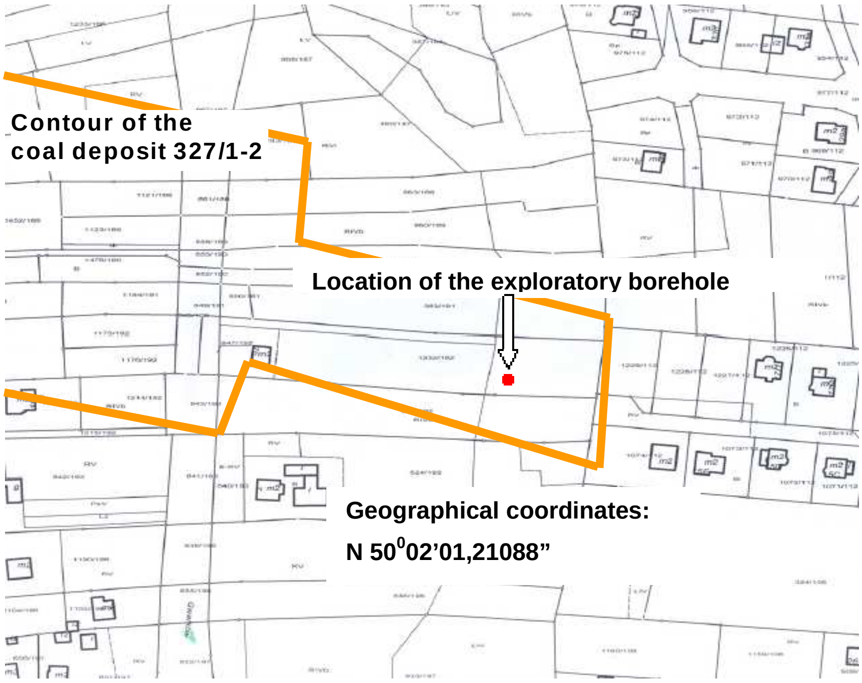

Figure 7. Location of the Żory mine research borehole

3.2.3 Construction of the exploratory borehole

The construction of the borehole included a design and an engineering part. Beside an optimal location, there were a number of other issues that required detailed planning, such as securing the stability of the hole, ensuring safety of the works and preventing potential hazards, enabling performance of geophysical investigations, providing proper isolation of the drilled water-bearing horizons and gas-bearing layers and first of all ensuring the execution of the methane capture tests. Moreover, the borehole drilling works and future operation of the borehole were also analyzed from the viewpoint of the potential influence on the environment . The outcomes of this analysis are presented in section 4.3.1. of the report.

Initially, the following construction parameters of the borehole drilling were set up taking into account the geological and hydrological site conditions:

- Holocene formation ≈ 10m b.s.l. (below terrain surface level), protected with casing pipes and a cement grout up to the surface (initial leading column),
- Holocene formation ≈50 m b.s.l. protected with casing pipes and a cement grout up to the surface,
- Neogen formation ≈150 m b.s.l which is ≈10 m in carboniferous formation protected with casing pipes and a cement grout up to the surface,
- Carboniferous formation a 140→215÷240 m b.s.l protected with casing pipes (liner) perforated between the section 155-215 m.

The heel of the shot was armed with a piping framing and a blow-out preventer during the drilling of the overlay from the depth of about 50 m and the carboniferous formation.
The following diameters of the borehole were designed for individual depth sections:

- depth 0,0 ÷ 10,0 m – Ø 457 mm pipes cemented to the surface,
- depth 0,0 ÷ 50,0 m - Ø 339,7 mm pipes cemented to the surface,
- depth 0,0 ÷ 140,0 m - Ø 244,5 mm pipes cemented to the surface,
- depth 130,0 ÷ 215,0 m - strainers Ø 168,7 mm (liner).

Also the site required preparations for the drilling. An access road has been hardened to enable transport of the drilling equipment. Power and water supply have been provided to ensure proper operation of the drilling works. The site has been also fenced to avoid trespassing and for safety reasons.

The drilling works started in March 2009. First a control excavation to the depth of 1,5m was performed. The actual drilling was carried out in 3 stages. First, the drilling was performed to the depth of 10m below the ground level with a pipe drill of Ø 610mm. Pipes of Ø 457mm diameter were installed in the borehole and a cement grout was injected between the pipes and the ground to cut off water infiltration from the water bearing layers. As a second step, the borehole section to the depth of 50 m was drilled with a drill of Ø 438mm. Pipes of Ø 339mm were installed and cemented up to the drilled depth of 50m. A drill of Ø 311mm was applied to perform the third section of the borehole to the depth of 145 m. Pipes of Ø 244mm were installed to the achieved depth. Similarly as in previous sections, cement grout was injected between the pipes and the ground. During the drilling, the flushing was changed twice.

Figures 8-10 illustrate different phases of the drilling works: initial phase - general view (Figure 8), some elements of the drilling set (Figure 9), the installation of the Ø 244mm pipes in the deepest section of the borehole (Figure 10).

Figure 8. Drilling starting phase - general view

Figure 9. Mixers and flushing pump

Figure 10. Installation of the Ø 244mm pipes in the borehole

The drilling works were completed in April 2009. The borehole was closed with DN250 PN25 gate valve, the boring rig and additional equipment were dismantled and the area was rearranged (Figure 11). In mid May 2009 a container station connected to the borehole outlet was mounted (Figure 12 and 13). It included devices and instruments for gas suction, analysis and flaring. The container station was divided into 3 rooms where the following equipment was installed: lift-and-force system, high temperature torch and gas content analyzers for CH_4, O_2 and CO_2.

Figure 11. Site after completion of the drilling works

Figure 12. DN250 PN25 gate valve securing the borehole outlet

Figure 13. The borehole and the container station after completion of the drilling works

An important element of the installation was a containerized flare with integrated gas analyzing system provided by LNG-Silesia company (Figure 13).

The containerized station included a set of machines, devices and instruments for suction, analysis and gas flaring. The equipment, controlling and measuring part and the burners were located inside the container (Figure 14) while the pressure measuring instruments were installed within the measuring section located outside - between the outlet of the bore hole and the container (Figure 15) .

Figure 14. Engine room: 1 – filter, 2 – dehydrator, 3 – flame terminator, 4 – Roots' compressor, 5 – quick closing valve, 6 – manual valve, 7 – hoses to burners

Figure 15. Meter circuit (orifice, differential, pressure and temperature sensor)

The container was divided into 3 rooms where the following equipment was installed:

- lift-and-force system
- high temperature torch
- gas content analyzers and control system

The rooms were thermally insulated and heated, and equipped with gas detectors. The basic elements of the equipment were:

- piston compressor (Roots rotary pistons) with regulated efficiency and all necessary technical devices, of a maximum capacity: 500 m^3/h
- gas analyzing system for CH_4, O_2 and CO_2
- high temperature torch with half closed combustion chamber, with natural draught and controls, as well as controls and flame terminator. Maximal power 5000 kW. Range of work: 25-60 % vol. of methane. Air inflows to the torch room through the shutters on the sides of the container.

Instruments and detectors/sensors:

- suction pressure control,
- pressing pressure control,
- torch temperature control,
- engine revolutions control depending on the pressure using the inverter,
- compensators on the pipelines connections,
- cut off fittings – quick-closing pneumatic valve,
- flame terminator,
- by-pass regulation with membrane regulator,
- gas filter,
- condensate separator with condensate pump.

Figure 16 illustrates the containerized torch/flare.

The meter circuit, consisting of the orifice and temperature, pressure, pressure difference transducers providing the parameters of the gas on the inlet to the container, was installed before the container. The following gas measurements were carried out :

- gas pressure in the deposit and its changes in time,
- chemical composition of the gas and its changes in time
- amount of the gas extracted from the borehole

During the work of the station, the gas was flared in the torch to minimize its harmful influence on the environment (Green House Gas effect).

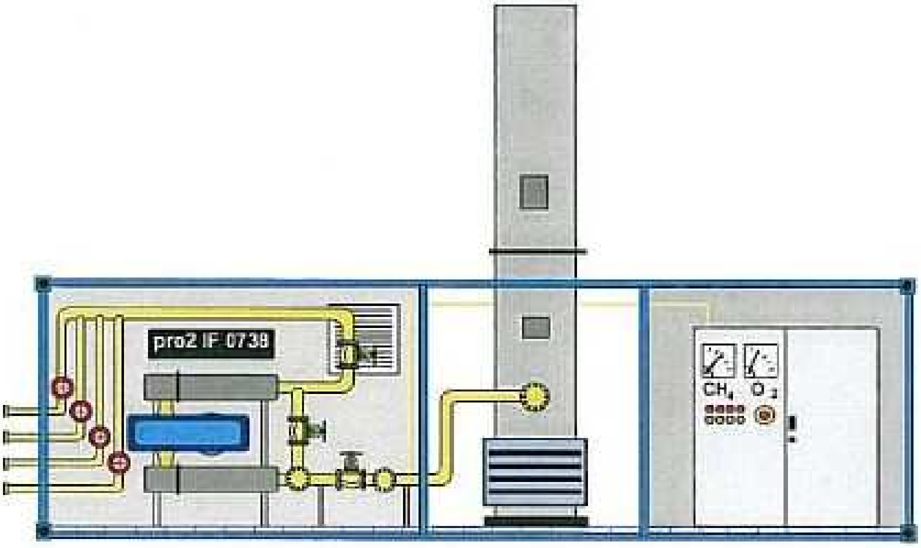

Figure 16. The diagram of the containerized torch/flare

3.3. Methods of methane capture and its characteristic

The aim for the methane capturing form the Żory research borehole was to determine its physical properties and composition, especially the efficiency of the gas flow and the methane and oxygen content from the viewpoint of its future use for LNG production as the key criteria determining the optimal way of utilizing the gas (heat and power energy production, LNG production). Conversion to LNG is economically and technically viable only if the methane content exceeds a certain value. Below this value, scenarios other than conversion to LNG should be considered mainly due to economic reasons. An additional factor determining an efficient liquefaction process is the content of oxygen. Below five CMM use scenarios are proposed from the viewpoint of methane and oxygen contents indicated as success criteria for each scenario. These success criteria have been assumed also for the methane capture tests.

Scenario 1 **CH_4 content below 40%**	- The use of gas is rather limited. - Installation for is purification and liquefaction will be extremely complicated and energy-consuming and will require high investment outlays and operational costs. - The only economically justified way of utilizing the gas of such composition will be combustion for heating purposes
Scenario 2 **CH_4 content 40-50%.**	Similarly as in scenario 1, conversion to LNG cannot be economically justified. An increased methane content compared to scenario 1 enables a viable utilization of the gas for combined heat and electric power production.
Scenario 3 **CH_4 content 50-70%,**	- Such a composition of CMM already enables its conversion to LNG. However due to low content of methane and a high content of content of oxygen, economic and technical analyses need to be performed in order to justify the economic viability of the process.

O_2 content below 8%.	- High oxygen content requires application of a catalytic reactor in which methane is combusted at the presence of oxygen and as a result carbon dioxide and water are produced. They must be removed from the process. - In consequence the system is characterized by high methane losses. Despite the fact that the waste gas can be further utilized for electric energy production to satisfy the needs of the installation, a large volume of it is burnt in the flare. Such a situation has a negative impact on the system performance and its economic effectiveness.
Scenario 4 **CH_4 content 70-80%,** **O_2 content below 5%.**	- Relatively high methane content in the inlet gas requires a much simpler and thus less energy consuming purification and liquefaction system. - Depending on the installation performance, reduced oxygen content can be removed either in a catalytic reactor or by cryogenic separation. - Both methods result in a significantly smaller methane losses then in Scenario 3, improving the performance and efficiency of the entire
Scenario 5 **CH_4 content above 80%,** **O_2 content below 3%.**	- The most favorable scenario from the viewpoint of LNG production. - Low oxygen concentration at high methane content has a positive impact on the economic factors of the investment. - Such gas composition requires relatively low investment and operational costs to ensure an economically viable LNG production even in a small scale installation i.e. 5000 gpd LNG.

As indicated above, the minimum requirements for considering CMM conversion to LNG include minimum methane content in CMM in the range of 50-70%, maximum oxygen content below 8%.

3.3.1. Protocol for gas sampling from the Żory borehole

Gas sampling was carried out in accordance with ISO regulations [4]. In general two phases of gas sampling were planned:

Phase 1 – consisting in an initial trial capture of the gas combined with testing of the equipment for monitoring the capture process and measuring the gas parameters

Phase 2 – proper gas capture and monitoring of its parameters to determine the chemical composition, physical parameters of the gas stream at the outlet and the volume of the obtainable gas resources.

Figure 17 presents the gas flow diagram i.e. from the borehole outlet to the combustion in the flare. Location of the control and some monitoring equipment is also indicated. Figure 18 presents the gas sampling point.

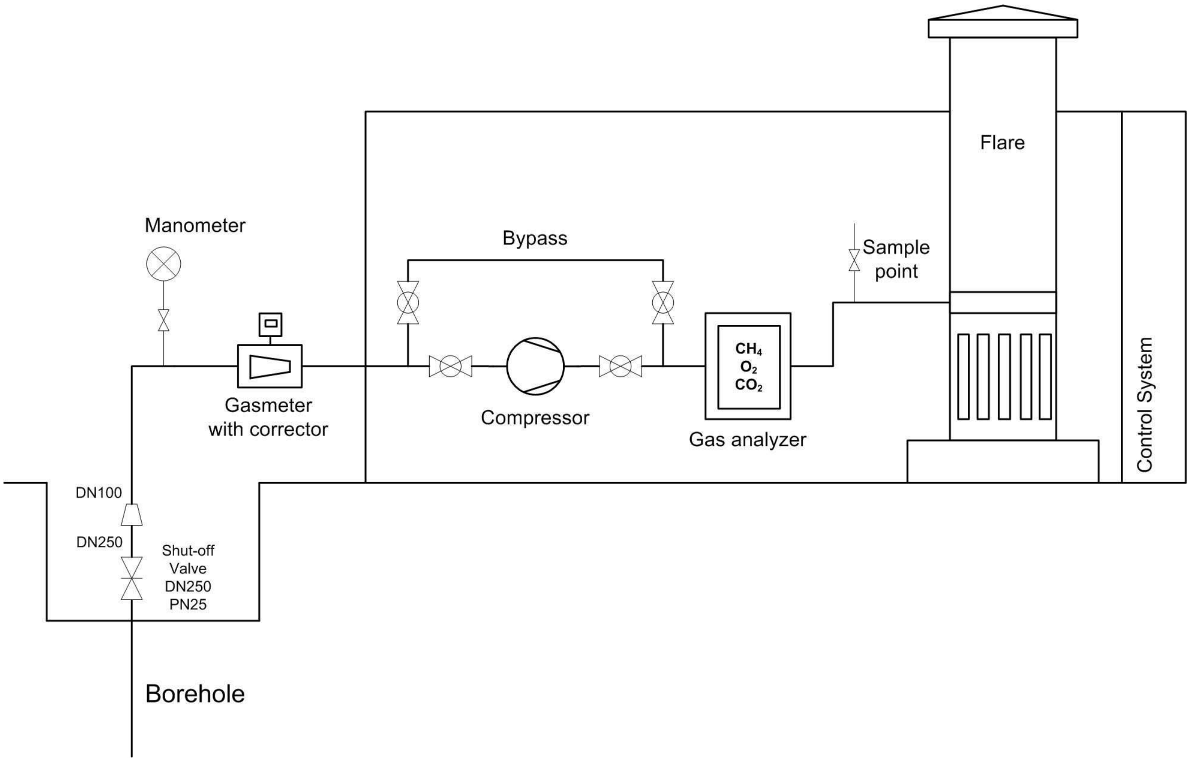

Figure 17. The Żory exploratory borehole gas flow diagram and the location of the sampling and monitoring equipment

Phase 1 was designed to last for about 8 hours and was considered as preparatory works leading to achieve the proper gas stream that will be subject for further analysis in Phase 2. Phase 1 did not assume any monitoring or analyses. Only at the end of the trial capture one gas sample was collected for chromatographic analysis to determine the parameters of the gas before its flowing into the corrector.

Phase 2 assumed performance of test captures in a form of sampling campaigns. Within each campaign gas was sampled on a continuous basis. To consider a test capture successful, a gas flow of stabilized efficiency had to be recorded for the period of at least 72 hours (3 days). A maximum of 5 capture trials (campaigns) were planned , the duration of each minimum 3 – maximum 7 days depending on the stability of the gas parameters.

Figure 18. Gas sampling point

3.3.2. Scope and type of gas analyses

The analyses of the gas sampled from the Zory exploratory borehole were focused on determining the chemical composition and key physical parameters such as gas flow in working and normal conditions, gas overpressure, etc.

Additionally, key external parameters such as temperature and atmospheric pressure were measured *in situ* by a small meteorological station. Simultaneously with the gas sampling chromatographic analyses were carried out. The data from the meteorological station were transferred to a computer for storage.

Data characterizing gas composition and data from the meteorological station were recorded in special data collection sheets. Data from the sheets were transferred to a computer database once a day. This procedure referred both for data collected *in-situ* and laboratory data from chromatographic analyses.

Chemical analyses

The chemical analyses consisted of CH_4, O_2, CO_2 concentration measurements carried out in the captured gas in 15- minute or more frequent intervals. Additionally, less frequently, hydrocarbons other than methane (ethane, propane, C6+) as well as nitrogen, H_2S, organic sulfur and sulfur total were measured. Six measurement campaigns of mercury content in the gas were also carried out.

Measurements of CH_4, O_2, CO_2 concentrations were carried out with Pro2 SAS1 analyzer, using NDIR (Non-Dispersive Infrared) method. The method relies on the energy absorption characteristics of a particular gas in the infrared region. Precision of the analyzer was +/- 2% for all the analyzed components. Time step was 5 sec. for CH_4, 10 sec. for CO_2 and 15 sec. for O_2.

Except mercury, the analyses of the remaining gases (including selected hydrocarbons other than methane) were performed using Chromatograph Unicam 610/50 with FID according to the established ISO procedure [5].

The samples for chromatographic analyses were prepared according to the established procedure [5]. Sampling was made at least 6 times a day, every four hours. The chromatographic analysis of the collected gas samples was made during the day i.e. from 7a.m. ÷ 2 p.m. at the laboratory of the CETUS – Energetyka Gazowa[1] by authorized personnel. Samples collected in the evening or at night were stored in a closed container located by the borehole and forwarded to the laboratory at 8 a.m. of the following day.

Mercury concentrations were analyzed with the use of RA-915$^+$ ANALYZER (Lumex Ltd). The apparatus is typically used for determinations of mercury vapor concentration in ambient air [6] as well as natural and industrial gases. The mercury analyzer operation is based on differential Zeeman atomic absorption spectrometry using high frequency modulation of light polarization. Mercury lamp is a source of radiation (λ=254 nm), placed in a permanent magnetic field. The mercury resonance line is split into three components (Zeeman mercury triplet: π, σ_-, σ_+). When mercury vapor is absent in the analytical cell, the radiation intensities of both σ_- components are equal but when mercury atoms appear in the analytical cell, the difference between the intensities of the σ components increase as the concentration of mercury vapors grows. Detection limit for mercury vapor concentration with the use of: multi – path cell was 0,2 [ng/m^3], single – path cell – 500 [ng/m^3]. Maximum mercury vapor concentration with the use of : multi – path cell – 20 000 [ng/m^3], single – path cell – 200 000 [ng/m^3].

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[1] Since 2005 the CETUS Laboratory has the status of validated analytical lab (Report 220/B/PFC/2004) of the Central Measurement and Research Laboratory of the Polish Oil and Gas Exploration and Mining Company PIGNIG S.A.

Measurement of physical parameters

Measurements of gas flow in working conditions (m^3/h) were recalculated into normal conditions (Nm^3/h) after temperature and pressure correction. To perform the measurements, a gas meter and collector were used. The selection of the equipment depended on the intensity of the gas stream at the borehole outlet. Setting the corrector with the chemical composition data took place after the first chromatograph analysis made during the trial capture. Data on the temporary gas flow (efficiency) in normal conditions and their recording in the sheet were collected during sampling for chromatographic analyses. The data were transferred to a computer database at least once a week.

Measurements of the gas overpressure were directly linked to the assessment of the exploitable methane resources. It was important to identify if there was overpressure in the borehole which would prove a continuous methane desorption process from the non-exploited coal beds and a simultaneous secondary saturation of the bed with methane migrating from the deeper coal deposits, cracks and faults. The overpressure measurement was carried out using a manometer installed at the head of the borehole. First measurement was made before the trial capture. Following measurements were made each time when the gas flow was stopped (instantly after the stopping and initiation of the capture) without any fixed timeshedule. If the interval between the capture was longer than 3 hours, the overpressure measurement was made after each 1,5 - 2 hour. The data from the measurement in situ was recorded in a data sheet and periodically transferred to computer data base.

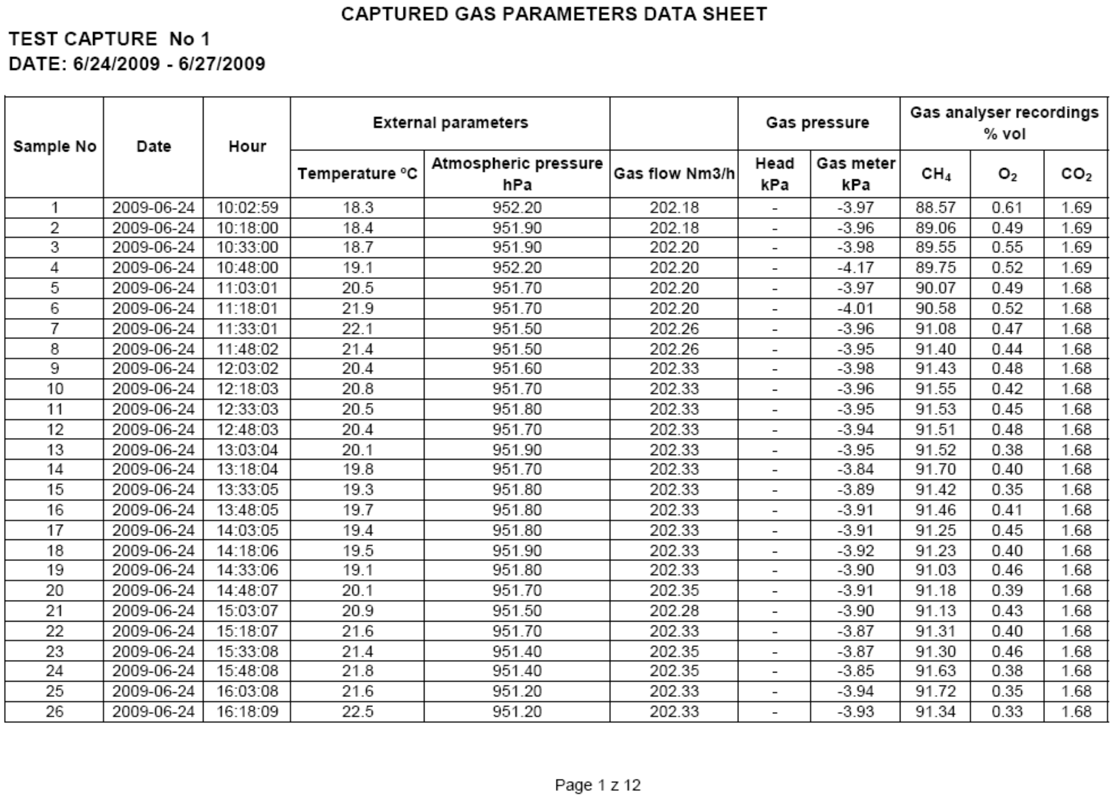
All the gas sampling on site and further procedures related to samples analysis as well as measurements of physical parameters were carried out according to respective Polish health and safety regulations.

4. Results

4.1. Physico-chemical parameters of the CMM from the Zory borehole

Gas samples were collected from the Zory exploratory borehole during five test captures. Each campaign lasted 3 days. The capture trails were performed in the period of June 24 - September 7, 2009. The following parameters were measured: temperature, atmospheric pressure, gas flow, gas pressure in the borehole, methane, oxygen and carbon dioxide concentrations. The measurement data were stored every 15 minutes by the data acquisition system. In total, 1434 data sets were collected during the measurement period.

Example of the captured gas parameters data sheet containing results obtained in the first measurement campaign is presented in Table 1.



CAPTURED GAS PARAMETERS DATA SHEET

TEST CAPTURE No 1
DATE: 6/24/2009 - 6/27/2009

Sample No	Date	Hour	External parameters			Gas pressure		Gas analyser recordings % vol		
			Temperature °C	Atmospheric pressure hPa	Gas flow Nm3/h	Head kPa	Gas meter kPa	CH_4	O_2	CO_2
1	2009-06-24	10:02:59	18.3	952.20	202.18	-	-3.97	88.57	0.61	1.69
2	2009-06-24	10:18:00	18.4	951.90	202.18	-	-3.96	89.06	0.49	1.69
3	2009-06-24	10:33:00	18.7	951.90	202.20	-	-3.98	89.55	0.55	1.69
4	2009-06-24	10:48:00	19.1	952.20	202.20	-	-4.17	89.75	0.52	1.69
5	2009-06-24	11:03:01	20.5	951.70	202.20	-	-3.97	90.07	0.49	1.68
6	2009-06-24	11:18:01	21.9	951.70	202.20	-	-4.01	90.58	0.52	1.68
7	2009-06-24	11:33:01	22.1	951.50	202.26	-	-3.96	91.08	0.47	1.68
8	2009-06-24	11:48:02	21.4	951.50	202.26	-	-3.95	91.40	0.44	1.68
9	2009-06-24	12:03:02	20.4	951.60	202.33	-	-3.98	91.43	0.48	1.68
10	2009-06-24	12:18:03	20.8	951.70	202.33	-	-3.96	91.55	0.42	1.68
11	2009-06-24	12:33:03	20.5	951.80	202.33	-	-3.95	91.53	0.45	1.68
12	2009-06-24	12:48:03	20.4	951.70	202.33	-	-3.94	91.51	0.48	1.68
13	2009-06-24	13:03:04	20.1	951.90	202.33	-	-3.95	91.52	0.38	1.68
14	2009-06-24	13:18:04	19.8	951.70	202.33	-	-3.84	91.70	0.40	1.68
15	2009-06-24	13:33:05	19.3	951.80	202.33	-	-3.89	91.42	0.35	1.68
16	2009-06-24	13:48:05	19.7	951.80	202.33	-	-3.91	91.46	0.41	1.68
17	2009-06-24	14:03:05	19.4	951.80	202.33	-	-3.91	91.25	0.45	1.68
18	2009-06-24	14:18:06	19.5	951.90	202.33	-	-3.92	91.23	0.40	1.68
19	2009-06-24	14:33:06	19.1	951.80	202.33	-	-3.90	91.03	0.46	1.68
20	2009-06-24	14:48:07	20.1	951.70	202.35	-	-3.91	91.18	0.39	1.68
21	2009-06-24	15:03:07	20.9	951.50	202.28	-	-3.90	91.13	0.43	1.68
22	2009-06-24	15:18:07	21.6	951.70	202.33	-	-3.87	91.31	0.40	1.68
23	2009-06-24	15:33:08	21.4	951.40	202.35	-	-3.87	91.30	0.46	1.68
24	2009-06-24	15:48:08	21.8	951.40	202.35	-	-3.85	91.63	0.38	1.68
25	2009-06-24	16:03:08	21.6	951.20	202.33	-	-3.94	91.72	0.35	1.68
26	2009-06-24	16:18:09	22.5	951.20	202.33	-	-3.93	91.34	0.33	1.68

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Table 1. Example of captured gas parameters data sheet

Figure 19 illustrates the correlation between the methane content and the atmospheric pressure at the beginning (Test Capture 1) and at the end (Test Capture 5) of the trails. It indicates that the methane content was high (periodically above 90%) but decreased throughout the experiment period to stabilize at the level of about 80%. However it should be indicated that the final use of the captured gas is not determined by the atmospheric pressure changes.

Figure 20 illustrates the correlation between the CO_2 and O_2 concentrations for Test Capture 1 and 4. A stable content of CO_2 at the level below 1.8 % was observed. The initial oxygen content was at the level of about 0.6 % and gradually decreased to the level around 0%. Gas chromatograph analyses showed average oxygen content at the level of 0.5 % during the intakes.

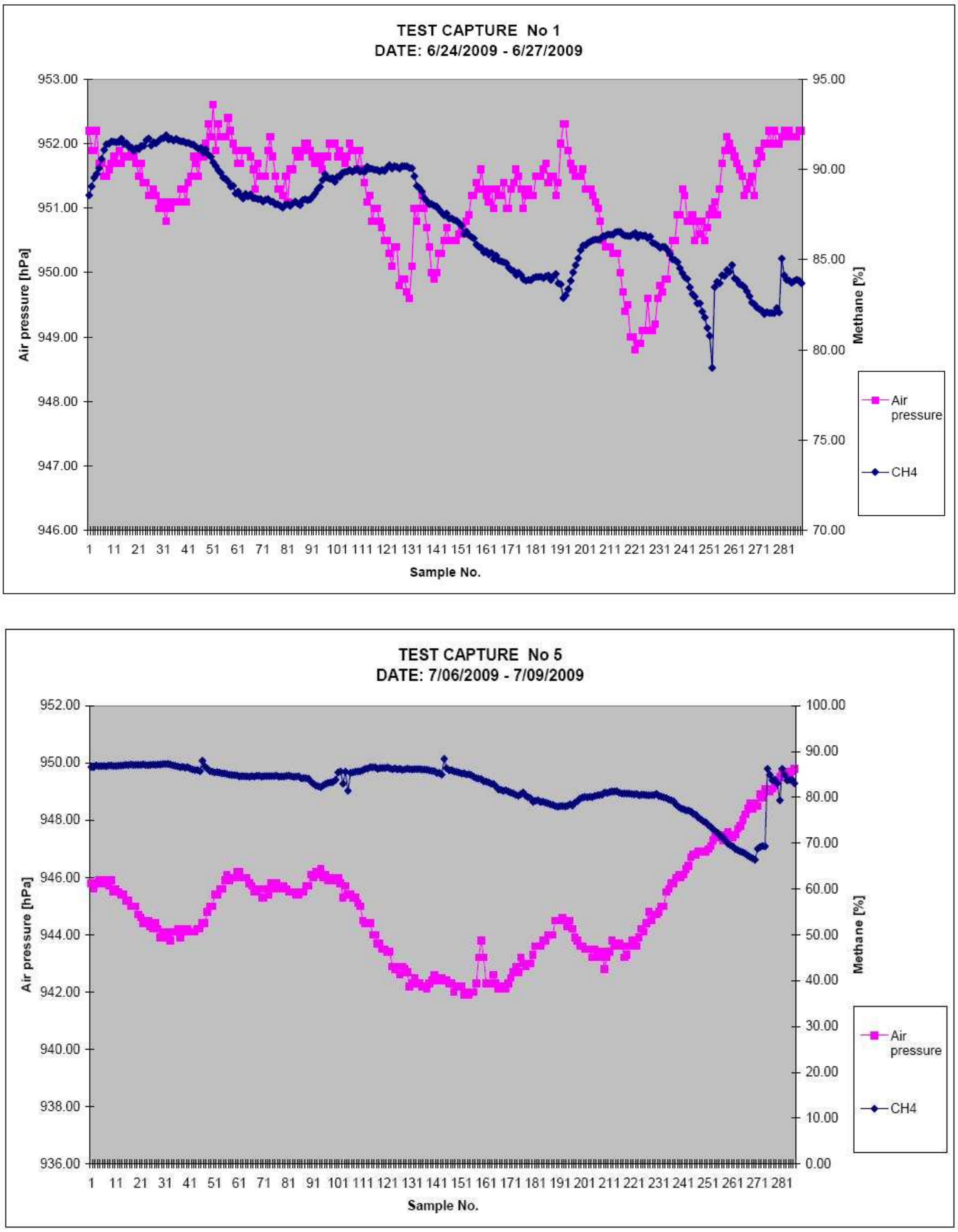
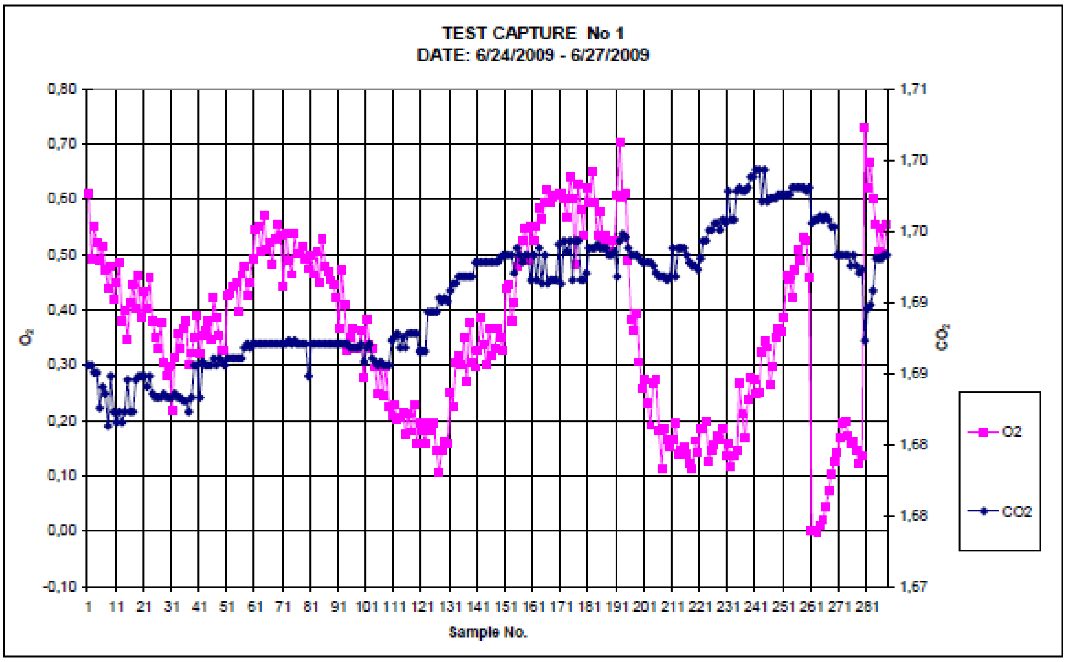


Figure 19. Concentration changes of methane from the Zory exploratory borehole and correlation with air pressure –Test Capture 1 and 5.

The obtained data showed that the average concentration of CH_4, CO_2, O_2 and N_2 that can be considered as reference concentrations for CMM from the Zory coal mine borehole were as follows: methane – 80%, carbon dioxide – 1,8%, oxygen – 0,5% and nitrogen – 17%



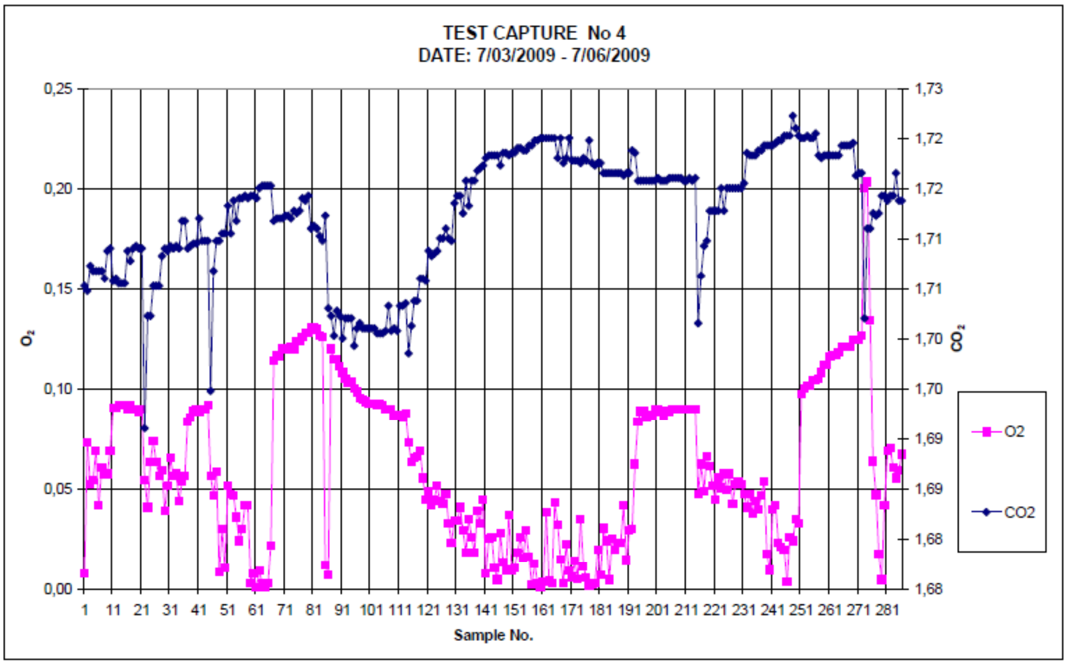


Figure 20. Concentration changes of CO_2 and O_2 in the gas from the Zory exploratory borehole – Test Capture 1 and 4.

During the test capture campaigns, gas samples were taken eight times for gas chromatograph analysis, to confirm the readings of CH_4 and oxygen gas analyzers. On the basis of gas chromatograph analysis it was proved that the difference between the readings of the gas analyzer installed in the flare and gas chromatograph outcomes were within the range of an acceptable error.

CMM from the borehole was also analyzed for the presence of some trace components such as C6+, ethane, propane, hydrogen sulfide, organic sulfur, sulfur total, mercury (Table 2). This data was important from the viewpoint of CMM conversion to LNG.

Table 2 presents the measurement data of the gas composition from the sampling campaigns carried out at the Zory exploratory borehole.

Table 2. Composition of the gas from the Zory mine exploratory borehole

Component	Unit	Value
Methane	% mol	79÷84
Ethane	% mol	0,01
Propane	% mol	0,01
C_6+	% mol	0,07÷0,13
Oxygen	% mol	0,28÷0,94
Nitrogen	% mol	14÷18
CO_2	% mol	1,3÷1,8
H_2S	mg/m^3	0,059
Organic sulfur	mg/m^3	0,406
Sulfur – total	mg/m^3	0,461
Moisture	g/m^3	9,712
Mercury: initial stage of borehole operation stabilized gas flow	ng/Nm^3	53 – 93; ±10.6 2.0 – 18.6; ±2.4

These parameters were assumed as input data for further analyses including the resources balancing and assessing the environmental effects of gas mining and conversion to LNG.

In general, the obtained data characterizing CMM from Żory borehole allow to categorize the gas as a good quality gas. Sulfur, mercury and moisture content were much below the acceptable values for pipeline gas. Heat of combustion, Wobbe index and heating value are high enough to classify this gas as a low quality pipeline gas. Only oxygen content can exceed acceptable limit (0.2%).

From the viewpoint of conversion into LNG, the parameters of the captured gas indicated that it should be rather easy to purify and liquefy. Therefore, the installation for LNG production may be simple, relatively cheap and economically viable to produce LNG on a small scale. Neither oxygen removal unit nor large CO_2 removal system will be required. Trace components (especially sulfur and mercury) could be removed on a small activated carbon bed. Also power requirements for the entire installation would be at a reasonable level independently from the implemented refrigeration method.

4.2. Balance of the CMM resources recoverable from the Żory area

The estimation the recoverable methane resources from the abandoned Żory coal mine was performed for area Żory 1 selected within the entire Żory site, located in its western and northern part (Figure 21). The investigated deposit covers the surface of ca 12,7 km^2 i.e. almost 76% of the total Żory site. It embraces three former mining sections „Z", „P" and „C" (Figure 3) including the part of the Żory coal mine, where mining works were conducted and for the data from geological investigations were available together with CMM data obtained from the exploratory borehole.

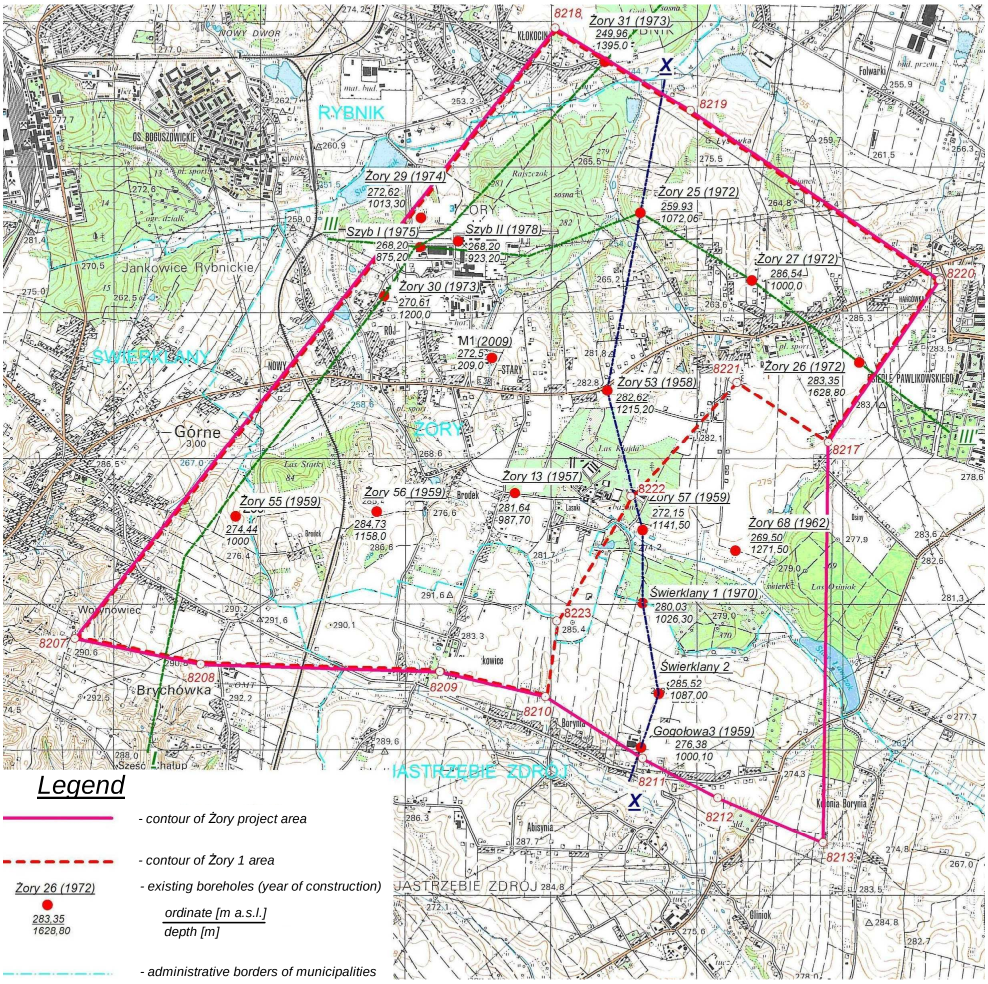


Figure 21. Location of the Żory 1 deposit

The Żory coal mine was a methane bearing mine, and its absolute methane bearing capacity i.e. the total amount of methane released from the mine was in the range of 46,3 m^3CH_4/min in 1987 to 17,1 - 18,7 m^3CH_4 per minute in the final stage of the operation (1995 - 1996). The mine used a demethaning system, which captured from 2,9 to 11,5 m^3 per minute . During the entire period of the mining activity i.e in the years 1979 – 1996, the mine demethaning system captured more than 51 MM m^3 CH_4 altogether.

Historical data on the geological conditions, including methane-related conditions of the Żory coal mine deposit together with the data collected during an over 10-year period of gas capture by the Jankowice coal mine as well as the results of tests performed at the exploratory borehole allowed to document quite well the deposit of methane accumulated in the goafs and headings of the abandoned Żory coal mine.

4.2.1. Methane bearing capacity of the Żory coal mine

The Żory coal mine was put to operation in 1979 and continued mining until its liquidation in 1996. Methane release accompanied coal extraction posing a significant risk factor (Figure 22). Until 1983 the volume of the mined coal increased to over 1,2 MM tons each year and decreased later to about 0,3MM tons in 1996. The maximum methane concentration reached about 24MM m^3 and was recorded in 1987. Later it decreased to 5MM m^3 in 1996. Maximum extraction volume and maximum methane bearing capacity did not coincide due methane release process caused by coal extraction and breaking beds and rock mass. Figure 23 presents the annual methane bearing capacity in the Żory coal mine as the coal extraction function. It illustrates the relation between mining and methane threat. As the figure presents, higher coal extraction was accompanied by higher methane concentration.

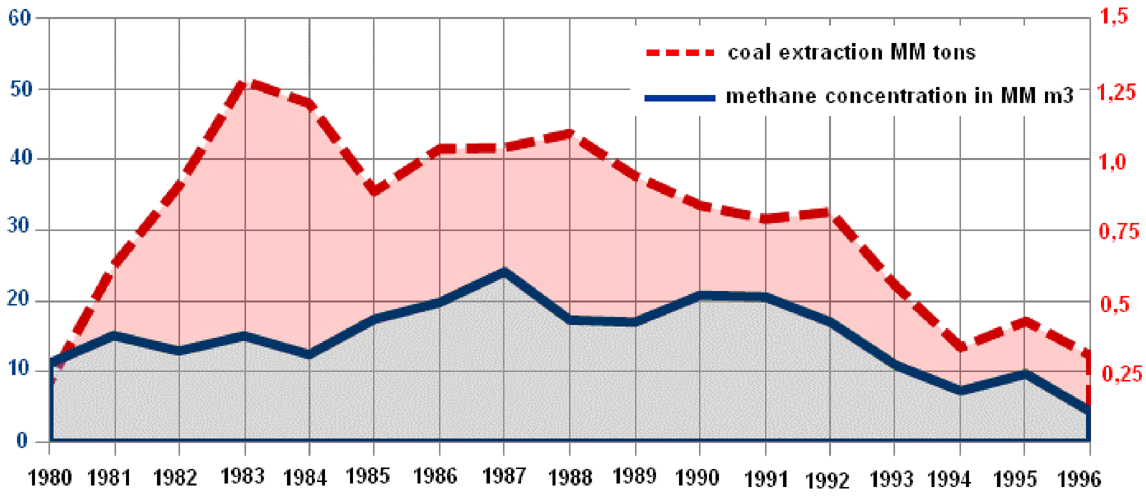


Figure 22. Methane bearing capacity and coal extraction in the Żory Coal mine during its operation

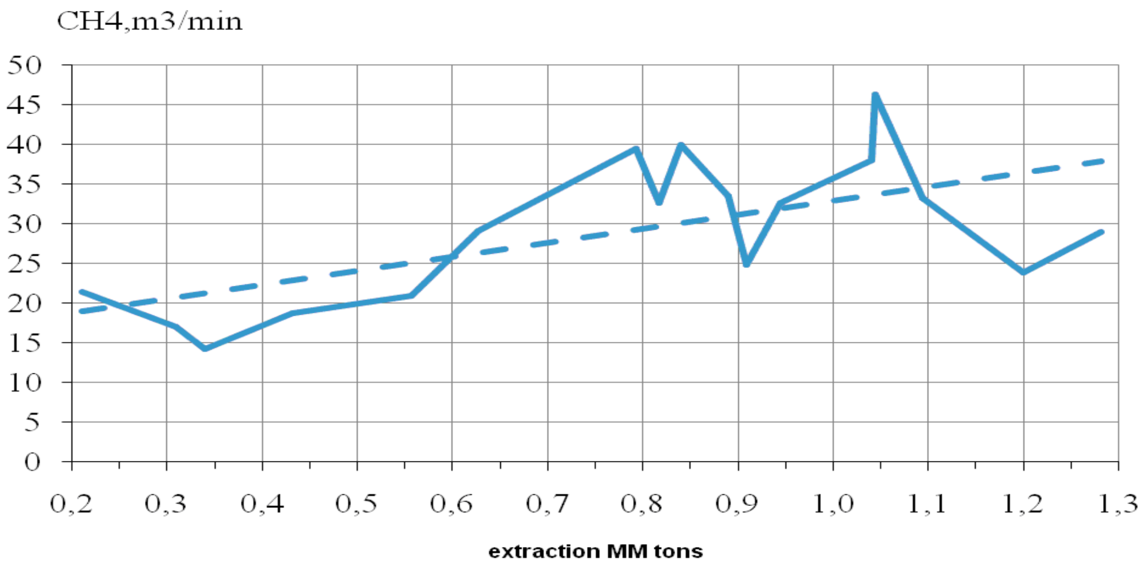


Figure 23. Methane bearing capacity as a function of coal extraction in the Żory coal mine during its operation

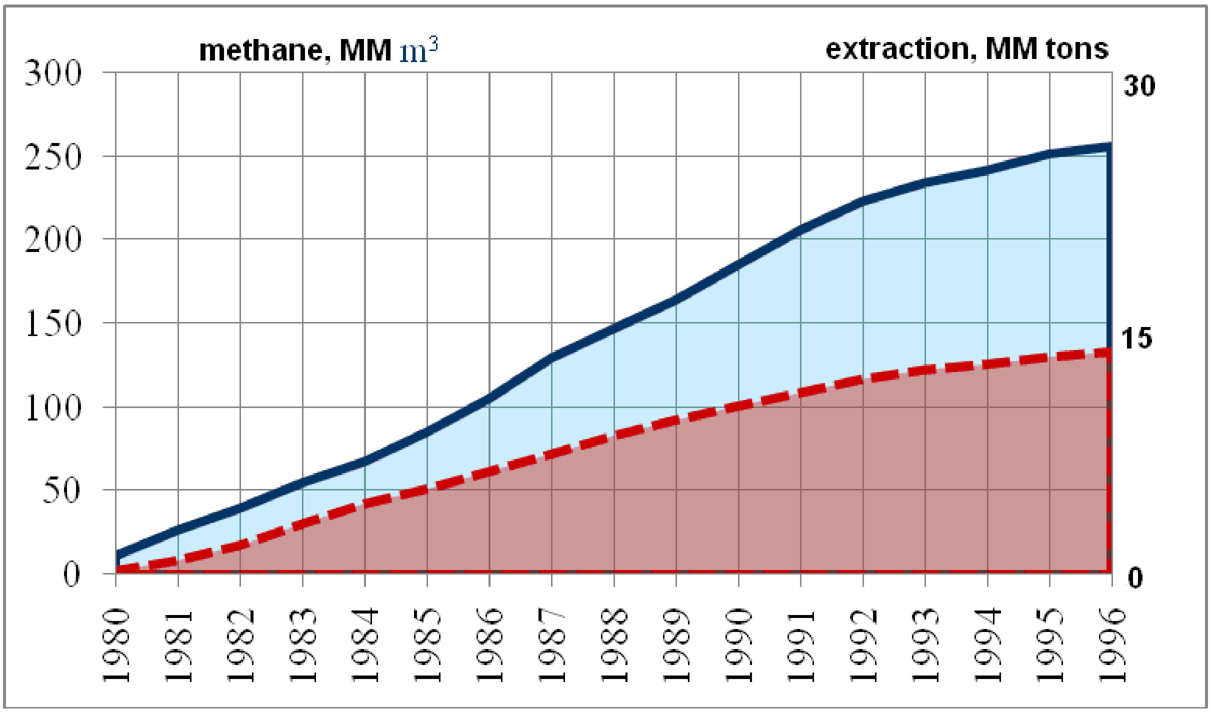


Figure 24. Total (cumulative) methane volume and total coal extraction in the Żory coal mine during its operation

The total (cumulative) volume of coal extraction and methane capacity released due to the process of mine's development and operation is shown in Figure 24. The line indicating the total methane capacity rose more rapidly at the beginning of the mine's operation, and slower when the termination of the operation was approaching.

4.2.2. Balancing criteria

For the purpose of documenting the dynamic resources of the adsorbed methane, „Żory 1" deposit was divided into 3 operation fields (sections):

- section „Z" (west part),
- section „C" (central part),
- section „P" (north part).

Table 3 shows that within sections Z, C and P, most of the boreholes for which the methane bearing capacity tests were done are located in section P, while for section Z the highest number of the methane bearing capacity determinations were performed, both in the boreholes and the mining headings.

Table 3. Evaluation of adsorbed methane accumulation conditions within „Żory 1" deposit

Section	Number of methane bearing capacity determinations in the section		Number of methane bearing determinations of beds in boreholes and mining headings	
	in boreholes drilled from the surface	in mining headings	In total to the depth of 705 m	the methane bearing capacity estimated M>1,31 m^3 CH_4/Mg of pure coal
P	23	84	107	88
Z	7	113	120	86
C	0	93	93	63
Total	**30**	**290**	**320**	**237**

The guidelines issued by the Polish Ministry of Environment [6] specify geological survey categories of methane deposits together with the conditions for qualifying the deposits to specific survey categories:

1. **category A** if the methane resources were documented through the operation boreholes, with the use of mass balance or statistical methods,
2. **category B** if there was at least 1 borehole made for 2 km^2, where necessary tests were performed for determining industrial resources,
3. **category C** if there was at least 1 borehole made for 8 km^2, where methane bearing capacity tests were performed.

The CMM resources of the Żory 1 deposit were calculated based on the following balancing criteria:

- maximal documented depth - 705 m b.g.l.
- minimal methane bearing defining the outline of the deposit area - 1,31 m^3/Mg c.s.w.
- minimal average methane bearing - 1,31 m^3/Mg c.s.w. (higher than residual).
- minimal coal bed thickness - 0,1 m.

The balancing was performed for the total desorbable CMM resources which can be recovered from the investigated area .

The assumed maximal documented depth corresponds to the depth of the water level located above the ordinate of - 411,4 m above see level i.e. above the level of 705 m b.g.l. Below the water level, desorption practically does not occur: no methane is liberated from the anthropogenic collector created in goafs and headings of the abandoned Żory coal mine. The desorption effect is associated with coal seams which thickness exceeds 0,1 m located within the range of mining works influence. Therefore, the minimal thickness of the coal seam was lowered from the recommended 0,6 m to 0,1 m.

4.2.3. Estimation of the recoverable CMM resources

Based on the historical geological data concerning the hard coal deposit of the Zory coal mine, the geological resources of methane as an accompanying mineral to the hard coal deposits of category B and C obtainable to the depth of 1500m were initially estimated on the level of 7 777,75 mln m^3 CH_4.

However, a detailed analysis of later survey data showed that the total desorbable methane resources associating the same coal deposits as above present to the depth of 1180m are on the level of 2 227,8 mln m^3, of which ca 2 027,8 mln m^3 is located at the depth range of 830 – 1180 m b.g.l. It can be thus concluded that most of the methane resources within the deposit are located at the depth of 830-1500 m in this part of the deposit where no mining activity has been performed. These resources however, due to technical and economic reasons shall not be subject to extraction at least in the nearest future.

The CMM resources recoverable from the Żory 1 deposit were estimated on the level of 156,290 mln m^3 of CH_4 in category C, including dynamic resources in the amount of 154,8 mln m^3 of CH_4, and static resources of free methane on the level of 1,505 mln $m^3$$CH_4$.

The recoverable CMM resources of over 150 mln m^3 located at the depth range of 400-705 m b.g.l, within the„Żory 1" deposit are large enough to make a positive investment decision. The parameters and amount of the gas prove its applicability either as fuel in a Combined Heat & Power unit or for conversion to LNG.

4.3. Environmental implications of methane recovery from the Zory borehole and its conversion to LNG

The scope of the environmental analyses performed in the project encompassed the overall influence on the environment of the methane extraction from the abandoned Zory coal mine , its processing to LNG as well as application and included:

- the phase of the borehole drilling and methane extraction process,
- the LNG production phase, concentrating on the assessment of the potential technologies of CMM drying and purification which could be potentially implemented at the Zory site,
- assessment of the avoided emission,
- analysis of the environmental effects of LNG application at a targeted market.

The borehole drilling and methane extraction process was analyzed from the viewpoint of the influence of these activities on the quality of air, water, soils and landscape and noise emission. These impacts are further described below.

The analysis of the environmental effects of LNG production from the Zory CMM was focused on conventional methods used for gas drying, purification and liquefaction taking into account their potential for application in Zory.

The environmental effects of the avoided emission due to the CMM capture from the abandoned Zory coal mine were analyzed as the most environmentally crucial benefit. It has been assessed that in 2009 the methane emission from the closed mine was on the level of 490 000 m^3 yearly. Recalculated to CO_2 emission, the capture and management of the obtainable methane resources from the Zory coal mine will help avoiding the emission of 7371 Mg CO_2/year. It should be underlined, that the mentioned methane emission volume was determined as of the year 2009 i.e. 12 years after closing down of the coal mine. The emission has been decreasing in time since the abandonment. Due to its importance, the analysis of the avoided CO_2 emission has been elaborated in details and presented as a separate section 4.4.

The target applications of the LNG produced in Zory were also considered in the project from the environmental effects viewpoint within the performed Case Study. They included the transport sector (e.g. diesel locomotives) and power industry. The results of the environmental implications of LNG application at the targeted market are presented in section 4.6.

4.3.1. Borehole drilling and gas extraction phase

Analysis of the environmental implications of the drilling works and the gas extraction from the Zory borehole included the following issues :

- emission of pollutants generated from fuel combustion (diesel) and the flare to the air,
- emission of noise caused by the work of the drilling machinery (drilling well engine, flushing pump engine, flushing mixer, compressor),
- generation of solid wastes (drilling waste, sediments from the flushing),
- emission of sewage (site personnel) and technological effluent (flushing),
- impact on groundwaters (the borehole intersects the existing aquifers),
- impact on the landscape.

The analysis showed that during the drilling phase pollutants emission to the air was generated by the work of the diesel engine of the rig and the flushing pump as well as at the stage of the gas test capture (flare). Emissions to the air at the operational stage of the borehole i.e. during gas extraction may be related to:

- gas discharge during testing or siphoning of the boreholes,
- functioning of the safety valves preventing excessive gas pressure,
- gas escapes through leakages in the pipes and equipment, especially through valves, joints and gaskets,
- emission of vapors from ethylene glycol regenerators which may include aromatic hydrocarbons and hydrogen sulfide.

Negative environmental effects were found to occur only over a limited period of time i.e. when the drilling work was performed and referred to the nitrogen oxides emissions which exceeded permissible standards.

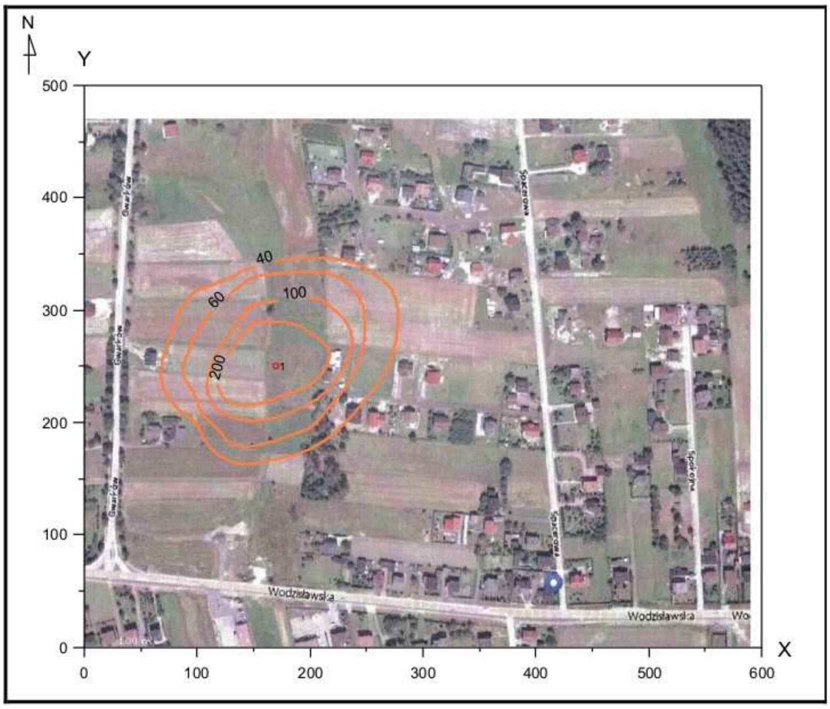


Figure 25 . Isolines of 99.8 percentile of maximum NOx concentrations (µg/m^3)

The observed exceedances of the permissible NO_x concentration levels (200 µg/m^3 as 99.8 percentile of max. conc.) were limited to the period of 11 days. The range of the area around the borehole where the concentration standard was exceeded is presented on Figure 25.

Similar maps presenting the results of the analysis of air pollutant concentration distributions were produced for benzene, sulfur dioxide, carbon monoxide and for suspended dust PM10. In the case of PM10, the maximum concentrations occurred in the distance of about 10 meters from the emission source, at wind velocity of 1 m/s from direction 6 (southern).

A negative environmental effect was identified for noise as the result of the drilling works (rig engine, flushing engine) and during the methane capture (compressor). Modeling calculations of noise dispersion showed (Fig. 26) that the permissible level might have been exceeded only during the drilling phase in the distance of 200m from the source. The exceedance occurred during the night when the permissible noise level in the vicinity of a residential area was 45 dB(A).

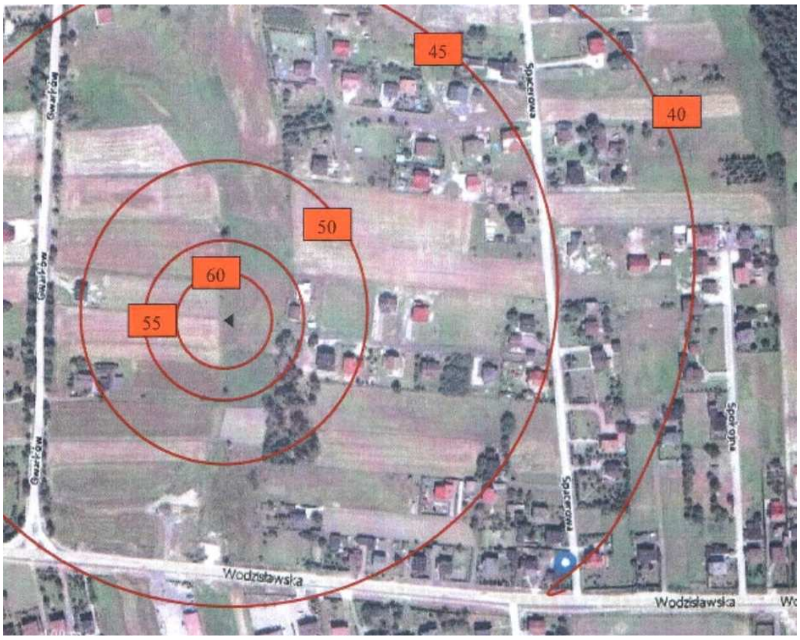


Figure 26 .Map of noise dispersion in the vicinity of the borehole – drilling phase; the values of the equal loudness contour in dB(A).

During the drilling phase solid waste was produced: drillings and flushing sludge. The total waste volume was about 75 m^3. This waste was not categorized as hazardous and thus was disposed at the local landfill site. After completion of the drilling works, the area around the borehole was restored and put in order. No permanent land deformation was left after removal of all the machinery used during borehole drilling.

The wastewater generated during the drilling from the flushing was pumped to the workings of the Zory mine at the final phase of the drilling. Its volume resulted from the amount of the water used during drilling and was over 300 m^3. The volume of the generated sewage was about 4m^3 , it was disposed at the wastewater treatment plant.

4.3.2. LNG production phase

The properties of CMM depend on the bed and the method of its recovery. They may vary over time and depend on the conditions of its extraction. The typical components of CMM include methane, carbon dioxide and sometimes nitrogen. Such substances as hydrocarbons of longer chains, water vapor, oxygen, hydrogen, carbon monoxide, helium, hydrogen sulfide, chlorine hydrogen, fluoride hydrogen, ammonium and mercury may occur in smaller or trace amounts. Similarly as in the case of natural gas, CMM requires purification before any application or processing including liquefaction to remove the undesired substances.

There is a number of conventionally used methods for natural gas purification prior to liquefaction which could be applied for CMM. A simple survey of the commercially available purification technologies was carried taking into account their applicability for the purification of gas from the Zory borehole for LNG conversion and the environmental impacts they may cause. The influence of both purification and liquefaction technologies on the environment was analyzed with focus on:

- emission to the air
- emission to the water
- generated waste streams
- noise emission
- generation of semi- and byproducts

Gas drying and purification

The obtained gas composition data indicate that converting the Zory CMM to LNG will require dehydration, removal of H_2S, CO_2 and mercury, degasolination and denitrification prior to liquefaction. Below the main reasons justifying these processes are briefly described.

Dehydration

The extracted gas contains some amounts of water vapor. Its content in CMM may pose serious problems in low-temperature (cryogenic) gas processing installations due to the condensation and formation of ice traps and crystalline hydrocarbon hydrates which may block the installation. Additionally, water content intensifies corrosion processes especially when accompanied by acid gases.

Acid gases (H_2S and CO_2) removal

Sulfur compounds must be eliminated from CMM due to the following reasons: toxic properties (both for household use and for catalysts in chemical syntheses) and metal corrosion (installation damages). Carbon dioxide in low temperature gas processing undergo solidification which may cause stoppage in the fittings.

Degasolination

Removal of C_3+ hydrocarbons is necessary since their presence intensifies the generation of solid hydrates which may reduce the throughput of the installation.

Denitrification

Gases with high nitrogen content represent much lower calorific value then low- nitrogen gases. The nitrogen elimination from the gas is necessitated primarily due to the frequent practice of mixing gases originating from different deposits. They must represent similar parameters in order to be combusted in the same burners.

Mercury removal

Removal from gas is necessary due to its toxic impact on the gas users and mercury corrosion of the gas processing installations (generation of metal amalgamates).

Table 4 below presents a list of the analyzed technologies together with the summary of their environmental impacts

Table 4. Environmental impact of selected methods of CMM purification (X indicates existence of an environmental impact)

Process	Emission To the air	Emission to the water	Generated waste streams	Noise Emission	Semi-, by-products
CMM drying methods					
Water vapor absorption by ethylene glycols	X	X X	X	X	X
Low temperature separation process (LTS)	X	X	X	X	X
Adsorption of molecular sieves		X	X	X	
Acid gas removal methods					
Absorption with a chemical reaction in water solutions of amines	X		X	X	
Sulfinol process	X		X	X	
Purisol process	X		X	X	
Adsorptive desulphurization on molecular sieves–with sieves regeneration	X		X		
Adsorptive desulphurization on molecular sieves –sieves regener. in SO_2 stream		X	X		X
Mercury removal					
Mercury removal method (activated carbon impregnated with sulfur)			X	X	

The environmental noxiousness of the methods of dehydrating CMM presented in Table 4 depends primarily on the composition of the raw gas e.g. the content of benzene, ethylene, toluene and xylene as well as on the size of the installation. That is why the final decision on the selection of the most environmentally appropriate drying method depends primarily on the technological issues. However, at this stage of investigation, adsorption on molecular sieves seems the least burdensome for the environment among the considered methods of CMM dehydration.

The environmental noxiousness of the methods of acid gas removal can be assessed as comparable and without any particular environmental risks. Theoretically, the smallest amount of contaminants is discharged to the environment from the method based on adsorption using molecular sieves.

Since the mercury content in the CMM obtained from the Zory site is small (below 0,001 mg/Nm^3), its removal will not be necessary for CMM conversion to LNG and because of that no negative mercury impact on the environment at the stage of CMM purification should be expected.

Liquefaction

The choice of the gas liquefaction technology depends on the desired efficiency performance of the installation, gas composition (content of CO_2, H_2S, N_2, heavier hydrocarbons) and its pressure. The following three hydrocarbon gas liquefaction technologies were analyzed from the viewpoint of their environmental impacts:

- classical cascade cycle,
- auto refrigerant cascade cycle (using mixed refrigerant of hydrocarbons extracted from the liquefied gas),
- decompression cycle with a turboexpander unit.

Classical cascade cycle.

The classical cascade process consists in cooling the natural gas in three refrigeration cycles. As refrigerants propane, ethane and methane are used. Feed gas stream purified from water and CO_2 content is cooled in the three successively lower refrigeration levels forming a cascade train.

After decompression each of the refrigerant streams (propane, ethane, methane) undergoes a successive, several-stage compression to increase the energy savings of the process. Low energy consumption is the primary advantage of the classic cascade method. About 0.5 kWh is used to liquefy 1 m^3 of gas. The drawbacks of this technology include a relatively large number of installation units of the train e.g. multistream thermal exchangers, compressors, pipes etc. as well as the need to control a large number of liquid streams, demand for clean ethane and propane together with the construction of adequate tanks to store them. All these requirements result in high operational costs of the installation.

Mixed refrigerant cascade cycle

This method is a classical cascade technology, however only one compressor and one refrigerant are applied. The refrigerant is a mixture of hydrocarbons extracted from the C_2+ fraction condensed in the “methane” part of installation. A pre-cooling using a propane refrigeration cycle is applied in the installation. The composition of the mixed refrigerant is selected in such a way as to enable condensation of an adequate part of hydrocarbons which will be sufficient to supply the low temperature demand resulting from the 2 and 3 exchangers balances.

A mixed refrigerant cascade train with propane cycle precooling consume about 0.6 kWh/kg LNG. It is by several per cent more than the classical cascade process. Despite that fact, mixed refrigerant cascade systems are more frequently applied as their key advantage are lower costs of both: investment (ca by 20%) and operation due to the application of only one compressor, less complicated pipage and number of the controlled fluid streams. Another strong point of this system is the production of the circulating refrigerant directly from the liquefied natural gas.

Decompression cycle.

The decompression cycle based installations for hydrocarbon gas liquefaction perform according to the principle similar to the classical Joule-Thompson natural gas liquefaction method (applied very rarely) and installations for liquid oxygen and nitrogen production by cryogenic air fractionation.

Gas liquefaction by decompression cycle is characterized by low efficiency; however it is simple and requires relatively low investment outlays. The key element of the process is turboexpander, in which 85% of the gas is decompressed and cooled to cryogenic temperature (obtained energy drives a compressor). This part of the gas is then used to condensate 15% of the gas directed to the exchanger before the turbine inlet. Reducing the gas pressure by six times inside the turboexpander, about 10% of it can be liquefied i.e. 5% remain uncondensed. This gas is fed into the stream at the outlet of the turbine.

Decompression cycle trains are usually built in locations where the energy needed for the process is cheep as the energy demand of these installations is much higher than in cascade cycles. Therefore, decompression cycles are mostly used for small installations to satisfy the peak demands.

The analysis of the methods used for CMM liquefaction concerning their influence on the environment was carried out similarly as for the CMM purification technologies. The summary of the results is presented in Table 5.

Table 5. Environmental impact of selected methods of CMM liquefaction (X indicates existence of an environmental impact)

Process	Emission to the air	Emission to the water	Generated waste streams	Noise emission	Semi- and by-products
Classical cascade cycle				X	X
Mixed refrigerant cascade cycle				X	X
Mixed refrigerant cascade cycle in multi-section spiral exchanger				X	X
Decompression cycle with turboexpander				X	X

The results of analysis of the liquefaction methods showed that they are non-emission technologies from the viewpoint of emission to the air, water and soil (streams of generated waste). An exception is the noise emission resulting from the application of compressors and/or turboexpanders in the installations. This equipment may cause exceedances of noise emission levels especially in areas where more restrictive standards are applied (e.g. residential areas). Due to the fact that the borehole at the Zory site is located in the vicinity of a residential area, the environmental impact assessment report should be carried out at the design phase of the LNG installation to identify if the permissible noise emission standards are not exceeded. If exceedances are stated, special acoustic screens must be installed.

It should be underlined that the performed qualitative analysis of the purification and liquefaction technologies was aimed primarily at indicating their environmental effects. A complete survey of technologies for the decision making purposes of selecting specific purification and liquefaction technologies for the Zory methane can be made only when a number of other key technical parameters which determine the choice are provided e.g. daily targeted throughput of the installation, its final location, etc. At this stage of research work, this data were not available being part of the process design phase.

Moreover, the performed analysis did not include the issue of energy demand of individual technologies, which is directly translated into their impacts affecting the quality of the environment. Both types of technologies require heat supply. The medium of heat supplied to the installations is mainly technological steam. The selection of the gas drying and/or purification method does not determine the source of the technological steam supply. This aspect is typically addressed at the stage of process design as it requires specific data on the available infrastructure and local conditions. The steam may be supplied from the distribution network or produced onsite in a boiler fired by any type of fuel. Thus, the emission points to the environment along with the types of emitted contaminants generated due to technological heat demand can be thus determined and assessed only at the stage of the process design.

4.4. Assessment of the avoided methane emission from the Zory coal mine

One of the key environmental benefits of the CMM capture from the Zory borehole is the avoided uncontrolled methane emission to the atmosphere from the abandoned mine. Methane emission from the mines is determined by a number of factors including the characteristics of the bed, implemented ventilation technologies, external conditions and the time since the mining operations abandonment. As mines are eventually abandoned they may be sealed by filling shafts or portals with gravel and capping them with a concrete seal. Vent pipes and boreholes may be plugged in a similar manner to oil and gas wells. When mining activity stops, the mine's gas production decreases, but the methane liberation does not stop completely and abandoned mines can liberate methane at a near-steady rate over an extended period of time. The gas migrates up through conduits, particularly if they have not been sealed adequately. In addition, diffuse emissions can occur when methane migrates to the surface through cracks and fissures in the strata overlying the coal mine.

4.4.1. Factors influencing CMM emissions

Within a coal bed, methane is stored both as a free gas in coal's pores and fractures, as well as on the coal surface through physical adsorption. As the partial pressure of methane in the fracture (cleat) system of the coal decreases, the methane desorbs from the coal and moves into the cleat system as free gas. The pressure differential between the cleat system and the open mine void provides the energy to move the methane into the mine. Driven by this pressure differential between the gas in the mine and atmospheric pressure, the methane will eventually flow through existing conduits and will be emitted to the atmosphere.

Many factors can impact the rate of methane emissions at both active and abandoned mines [8,9]. The most important factor is the total gas (methane) content of the coal, which has been directly linked to methane emissions from mining activities. The time since abandonment is a critical factor affecting an abandoned mine's annual emissions, as the mine's emissions decline steeply as a function of time elapsed. National Coal Board [10] and EPA [11] developed a decline curve (Fig.27.), which describes the rate at which methane continues to desorb from the coal after abandonment, moves into the mine void, and is eventually released to the atmosphere.

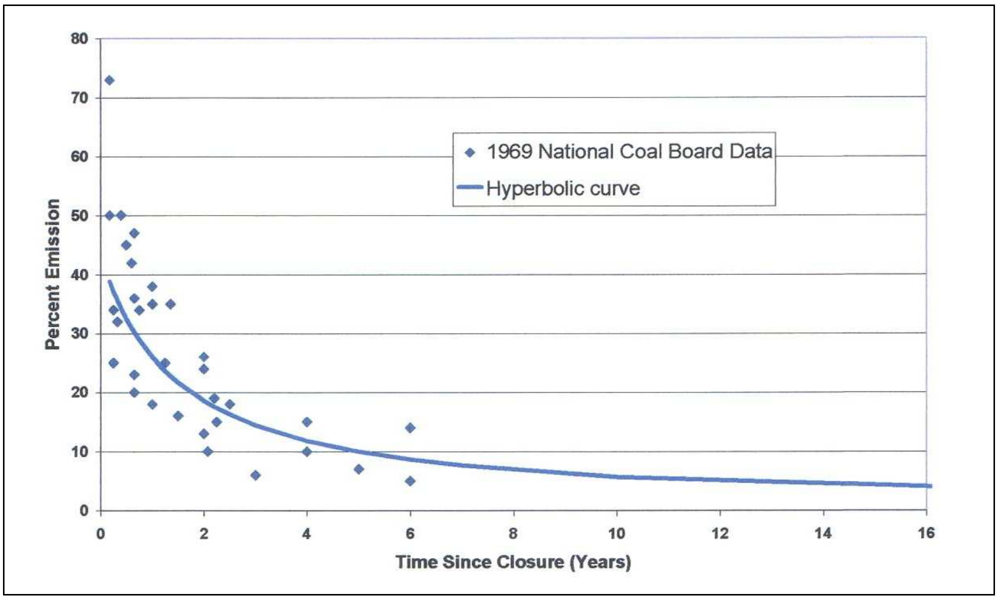


Figure 27. Graph of hyperbolic methane decay function and time since a mine closure [10]

The decline curve on Fig. 27 is strong function of time: the methane emissions rate decreases rapidly in the years immediately after a mine closure, and flattens out after several decades. Other factors impacting the rate of methane emission include mine size, flooding, sealing, and the coal’s permeability, porosity, and water saturation.

The template for calculating abandoned mine methane emissions is based primarily on the status of the mine, whether flooded, vented, sealed, or unknown. Emissions calculations for each type follow a similar sequence of steps. To forecast methane emissions over time for a given mine, one must characterize the gas production of that mine as a function of time (e.g. a decline function), and initiated at the time of abandonment. Ventilation air methane emissions rates from active mines are used as in indicator of a mine’s initial emission rate at time of abandonment.

Estimating emissions from an abandoned mine for any given year after its closure depends upon the status of the mine: whether it is open to the atmosphere through one or several vents, flooded, or partially sealed. Seals have an inhibiting effect on the rate of flow of methane into the atmosphere compared to open-vented mines. The total volume of methane emitted will be the same, but it will occur over a longer period. Accordingly, this methodology treats the emissions prediction from a sealed mine in a similar manner to emissions from a vented mine, but using a lower initial emissions rate that depends on the degree of sealing.

4.4.2. Estimation of methane emission

Methane within the Zory mine exists in two forms. The first form is free methane that fills up the abandoned workings, conduits, clefts, and fractures in the coal and rock. The second form is the methane absorbed in the micropores of the coal. According to reports prepared prior to the mine abandonment, the Żory CMM are located between the depths of 100 and 1,225 meters and amount to ca 2 billion m^3 (see section 4.3.3.)

The migration of methane from the abandoned Zory mine occurs through the abandoned workings and conduits as well as the rock mass. The methane also travels to the neighboring active mines. To assess methane emission from the abandoned Zory coal mine the hyperbolic curve (Fig.27) as well as the following equation were used:

$$F=65/(t+1.5)$$

where: *F* is the proportion of the operating emission (%), *t* the time in years.

The analysis of the curve showed that methane emission rapidly dropped to the level of 40% of the emission from the operating mine after the abandonment of the mining activities. After two years the emission was on the level of 20%, after 5 years – 10% and after 13 years it amounted 5% with a tendency of gradual decline. Thus methane emission load from the abandoned mine depends primarily on the emission before the closure and the number of years since the abandonment.

The Zory coal mine was closed down over 12 years ago so it can be assumed that the present methane emission is on the level of 5% compared to the emission from the operating mine. Table 6 includes data on methane emission and the amounts of the mined coal during the mine operation. The data were used for methane emission calculation after the mine abandonment.

Table 6. Methane capture and coal extraction during the operation of the Żory mine

Year	Amount of mined coal	Average absolute CH_4 bearing capacity		Annual CH_4 emission	CH_4 captured by demethaning systems
		Achieved	Predicted		
	Mg/day	m^3 CH_4/min.	m^3 CH_4/min.	m^3 CH_4/rok	m^3 CH_4/min.
1980	3500	21.4	131.25	11 247 840	4.55
1981	3500	29.1	59.30	15 294 960	4.40
1982	3500	24.9	35.00	13 087 440	2.70
1983	3500	29.0	28.92	15 242 400	5.60
1984	3500	29.9	25.52	15 715 440	9.80

1985	3500	33.5	48.13	17 607 600	8.10
1986	3500	38.0	46.67	19 972 800	10.30
1987	3500	46.3	56.63	24 335 280	11.60
1988	3500	33.2	38.89	17 449 920	6.40
1989	5150	32.7	40.05	17 187 120	3.40
1990	5000	37.9	39.86	19 920 240	3.60
1991	4700	39.5	42.00	20 761 200	7.95
1992	5500	39.9	44.62	20 971 440	8.00
1993	4600	21.0	46.39	11 037 600	5.83
1994	4950	14.2	46.84	7 463 520	5.20
1995	4650	18.8	44.62	9 881 280	4.20
1996	4400	18.7	43.56	9 828 720	4.35

Assuming the initial methane emission before the mine closure on the level of 9,800,000 m^3/year, methane emission for the year 2009 was calculated as follows:

$$E_{CH4} = 9\ 800\ 000 * 0.05 = 490000\ m^3/year$$

Determining the methane emission using the indicator of 6 m^3/Mg of mined hard coal [12] the following methane emission was calculated:

$$E_{CH4} = 0.05*4400*6 = 1320\ m^3/day = 481800\ m^3/year$$

Both calculation methods provided quite similar data on methane emission from the abandoned Zory coal mine obtained for the year 2009. Therefore the emission value of 490,000 m^3/year has been adopted for further calculations. It should be underlined that the mentioned methane emission volume was determined as of the year 2009 i.e. 12 years after closing down of the mine. This volume has been decreasing since the mine abandonment.

Methane capture at the Zory site for conversion into LNG will cause a negative pressure in the void space of the abandoned mine which practically eliminates the up-to-date uncontrolled gas emission through the shafts and conduits and thus reduces the greenhouse effect. Therefore, it can be assumed that the total yearly emission for 2009 (12 years after Zory coal mine abandonment) amounted 100% of the assessed methane emission load to the air i.e. ca 490,000 m^3/year = 351 Mg/year (7371 Mg CO_2/year when recalculated to CO_2 emission).

4.5. Analysis of the LNG market in Poland and the LNG application potential

One of the objectives for the Zory Coal Mine Project was to identify the most promising application of LNG produced from the Zory borehole taking into account the economic and technical issues as a background for potential investment opportunities. To define this, a study was carried out which contained a broad analysis of the Polish gas market and its management mechanisms together with the key actors. The history of the fuel prices was also analyzed to gain a better understanding of the economic situation at the Polish fuel market. A general analysis of the gas market served as a background to a more focused analysis of the LNG market in Poland and the LNG application potential. The performed analysis of the Polish LNG market provided background for a case study of a targeted market and a potential client a local railway company, as a potential client interested in converting diesel engines to LNG. The case study is presented in the following section.

The analysis of the LNG application potential was based on the market data available for the years 2006, 2007, 2008 and the 1st quarter of 2009. These years seemed sufficient to generate a reliable picture as they constituted a representative period of time. The following fuels were selected for the analysis:

- light heating oil, natural gas and propane – as fuels used for technological processes,
- LPG and diesel- as fuels used for vehicles.

The criteria for this selection included LNG price competitiveness in relation to these fuels. Another criterion for the selection was related to the technical aspects i.e. the possibility of making a relatively easy, quick and cheap modernization of the devices and entire systems in order to use LNG as primary fuel. In majority cases, the modernization is limited to the construction of a gas system and replacement (or modernization) of burners in thermal devices (water and steam boilers, rotary and pusher furnaces) with no need to modernize or replace the entire thermal devices, which would constitute significant costs.

4.5.1. Fuel prices

The main determinants of the fuel pricing trends in Poland are the global crude oil prices and the PLN/USD exchange rate. Data reflecting changes of these factors was analyzed. To make the analysis clear, fuel prices were standardized and calculated according to the same unit i.e. PLN/GJ, The historical data related to the light heating oil were obtained from the Poland's largest oil producer company PKN Orlen, liquid propane gas (LPG) prices data originated from the e-petrol portal, whereas natural gas prices, regulated by the Energy Regulatory Office (Urząd Regulacji Energii - URE), originated from Polish Oil & Gas Company (Polskie Górnictwo Nafty i Gazu – PGNiG) and the tariffs of distributing companies approved by URE.

There are two more factors which also influence the fuel price:

- costs of transmission and distribution, with a justified return on capital invested in that activity;
- costs of business activity related to the storage of gaseous fuels, including construction, developing and modernization of repositories for gaseous fuels.

Figure 28 illustrates a comparison of prices of the analyzed fuels recalculated into the same currency and unit: PLN/GJ of chemical energy in relation to the calorific value (1 GJ = 947 817,1 BTU). This allows for a direct comparison of all fuels independently from the state of aggregation, individual fuel density, etc.

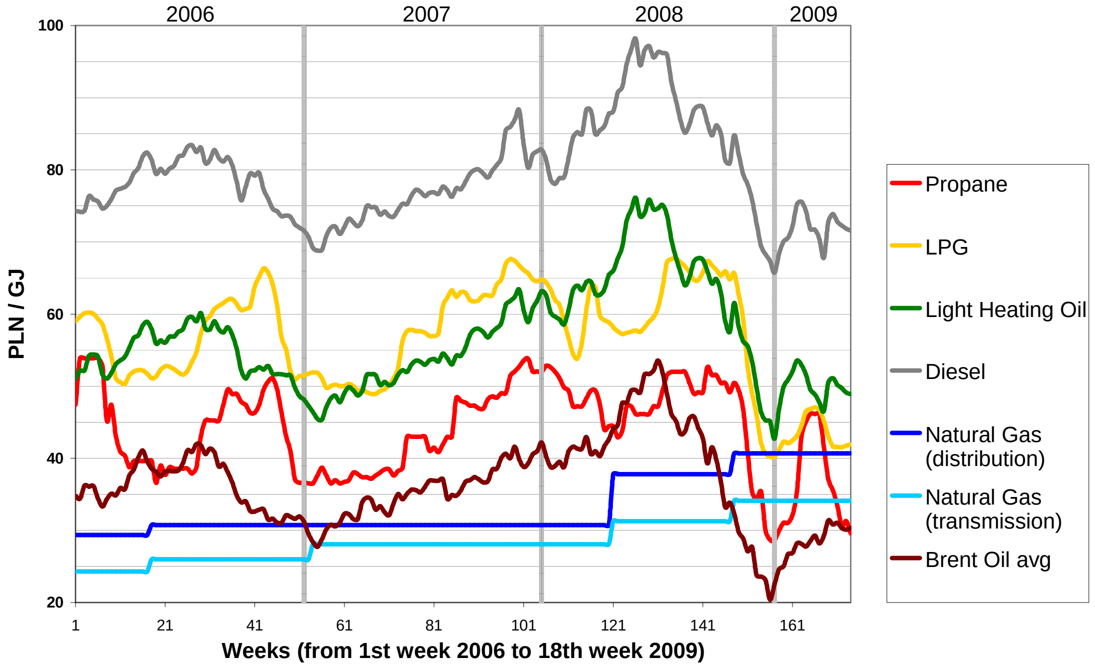


Figure 28. Comparison of prices (PLN) of analyzed fuels in relation to unified energy unit (GJ) within the period 1st January .2006÷30th April 2009 (prices do not include the value added tax -VAT)

The LNG price for end-users offered by LNG producers and distributors must be calculated individually, taking into consideration the costs of the currently used fuel, investment expenditures required for equipment modernization/adaptation and operational costs. An attractive price for LNG at minimum required investment for conversion into new fuel and operational costs maintained at an unchanged level may be about 5÷15% lower than the costs of the conventional fuel (competitiveness to heating oil and propane). When more investment outlays are required, the LNG price should be about 15÷40% lower. Such a situation takes place when buses or locomotives are modernized, as the modernization is viable when LNG is 30÷40% cheaper than diesel.

4.5.2. Gas market in Poland

The gas sector commercialization process in Poland began in 1998 when the state-owned enterprise – Polish Gas and Oil Company was transformed into a joint stock company owned exclusively by the State Treasury - PGNiG S.A. Simultaneously, the President of the Energy Regulatory Office began the process of granting concessions to companies from the gas sector. Thus, particular market activities were formed in the "gas chain", which in turn led finally to the development of the current structure of the Polish gas market:

GAS SECTOR → exploration and extraction
→ production
→ transmission
→ distribution
→ trade and storage

Despite the abovementioned transformations, Polish gas market is still highly monopolized by one group - PGNiG S.A. which, directly or indirectly, through its dependent entities, deals with all these activities and covers about 98% of the gas market. Thus Polish gas market is a single seller market and prices and tariffs need to be regulated.

At present, Poland consumes about 14 billion m^3 of natural gas per year. The most numerous group of gas end-users are households while the largest volumes of gas are consumed by industrial clients. Figure 29 presents the structure of gas consumption in Poland.

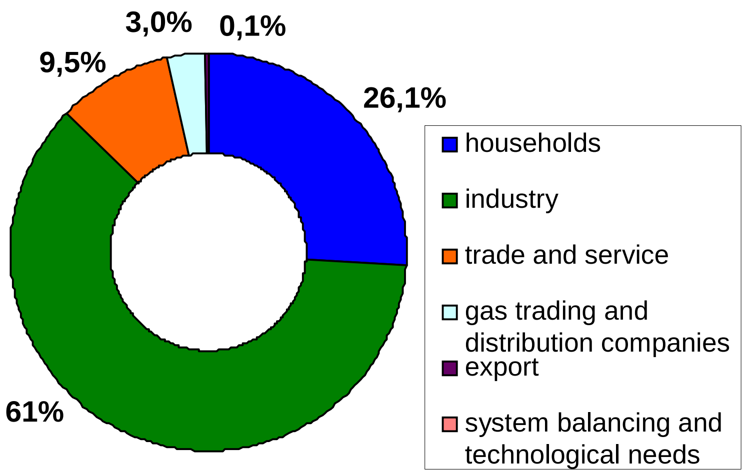


Figure 29. Structure of gas consumption in Poland

About 70% of gas used in Poland is imported from abroad, 30% is extracted in Poland Polish Oil and Gas Company [PGNiG] imports gas from Russia, Germany, Ukraine, Czech Republic and Central Asia. In 2008, the amount imported from Russia reached 68,8% of all imported gas supply, 23,2% from Central Asia and 8% from Germany. The supplies from Ukraine and Czech Republic were less than 0,1% of the total supply. PGNiG extracts natural gas in 12 gas mines and 9 oil-and-gas mines located in the region of Zielona Góra, and in 25 gas mines and 21 oil-and-gas mines in the Sanok area. Nitrogenized gas extracted in other regions of Poland like the Lower Silesia, Lubusz and Wielkopolska is further processed at the Odolanow gas processing plant. Table 7 shows the amounts extracted and imported by PGNiG in the years 2005, 2006, 2007 and 2008.

Table 7. Amounts of gas extracted and imported by PGNiG in the years 2005-2008

Natural gas supplies in Poland								
Source	**2005**	**%**	**2006**	**%**	**2007**	**%**	**2008**	**%**
	MM m^3		**MM m^3**		**MM m^3**		**MM m^3**	
Own production / extraction	4 318,1	30,8%	4 277,1	29,9%	4 276,0	31,5%	4073,9	28,4%
Import	9 690,6	69,2%	10 028,4	70,1%	9 286,6	68,5%	10264,2	71,6%
Russia	6 340,3	65,4%	6 839,7	68,2%	6 219,2	67,0%	7056,7	68,8%
Germany	330,6	3,4%	477,5	4,8%	783,6	8,4%	825,3	8,0%
Norway	485,1	5,0%	360,1	3,6%	-	0,0%	0	0,0%
Ukraine	1,2	0,0%	3,9	0,0%	4,2	0,0%	4,8	0,0%
Czech Republic	0,3	0,0%	0,3	0,0%	0,3	0,0%	0,2	0,0%
Central Asia	2 533,1	26,1%	2 346,9	23,4%	2 279,3	24,5%	2377,2	23,2%
Uzbekistan	nda	nda	2 308,4	23,0%	2 279,3	24,5%	0	0,0%
Turkmenistan	nda	nda	38,5	0,4%	-	0,0%	2377,2	23,2%
Total	**14 008,70**	**100,0%**	**14 305,5**	**100,0%**	**13 562,6**	**100,0%**	**14 338,1**	**100,0%**

nda – no data available

Except from PGNiG S.A., gas is extracted by several independent entities: Petrobaltic S.A. which owns an exclusive license to search and exploit deposits of hydrocarbons within the Polish area of the Baltic Sea covering about 30 000 km^2, EuroGas Polska Sp. z o.o., FX Energy Poland Sp. z o.o., RWE Dea Polska Oil Sp. z o.o., CalEnergy Gas Polska Sp. z o.o., CalEnergy Gas Polska Sp. z o.o. and Energia Zachód Sp. z o.o.

Majority of the gas trading companies sell gas via their own, local distribution networks, thus creating alocal monopole. The largest ones in terms of the gas volume are: ENESTA SA, G.EN., Gaz Energia SA, Media Odra Warta Sp. z o.o., KRI SA and EWE Energia Sp. z o.o. In 2008, only one gas trading entity - Handen SA – used a TPA (Third Party Access) rule[2]. Furthermore, there are new companies trading gas in liquefied form (LNG) without using the gas network at all.

There are many other entities dealing with gas trade, however majority of them purchase gas from PGNiG and resell it to end-users via own local pipelines. Other market participants include entities which do not have own pipelines but use TPA policy, which was first time applied in Poland in 2008.

Polish gas market is still a *single buyer market* as PGNiG SA incorporates all activities related to the so called gas chain – transmission, production, import, trade, storage and distribution. Each of these areas is still dominated by PGNiG. Apart from historical aspects, this situation is determined by several factors, such as the obligation of companies importing gas to Poland to keep gas reserves in repositories in Poland (owned by PGNiG), the fact that repositories and storage services are not available in Poland, limitations of transmission network, lack of legal regulations related to gas market in Poland. Current situation determines the selection of the applied regulatory tools e.g. natural gas prices are "tariffed" i.e. regulated in Poland. The implementation of tariffs makes the market less attractive for new gas trading companies and constitutes a real barrier for new traders. Other factors impacting the situation include the inter-system connections and cooperation of Polish system with the systems of other operators. At present, this cooperation is rather marginal and does not allow transmitting gas from other markets.

On the background of the entire structure of the Polish gas sector, an attempt was made to characterize the present LNG market.

4.5.3. LNG market structure and its key actors

Production statistics presented by PGNiG, within last years show that in 2005 17,6 MM scm were produced, in 2006 – 19,9 MM scm, in 2007 - 21,7 MM scm and 20,1 MM scm in 2008 [13]. Table 8 presents the key Polish LNG market actors.

Table 8. Key Polish LNG market actors and their areas of activity

Company	Activity
Polskie LNG Sp. z o.o. based in Świnoujście -	The company is 100% owned by GAZ-SYSTEM S.A. and its task is to build and operate the LNG terminal in Świnoujście. The terminal will receive and re-gasify LNG from potential

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[2] TPA rule enables a third party to use the grid owned by energy company without the need to purchase power from them. Its purpose is to allow for development of competitiveness at the power market.

	suppliers North Africa and Middle East At the initial stage, LNG terminal will allow receiving 2,5 billion m^3 of natural gas per year. Later this amount may be increased to 5 or even 7,5 billion m^3 per year depending on the demand.
CP Energia SA based in Warsaw	The company specializes in natural gas trade and distribution and manages gas pipelines. It owns over 100 km of pipelines within Poland. The Company offers also natural gas supplies in liquefied form (LNG) imported from Russia. In 2008 CP Energia purchased Krioton – a company, which is building LNG production plant close to Jarocin. The plant will be located close to a gas mine, the source of gas for the liquefaction plant. The start-up is scheduled for 2009 and the planned capacity is 100 tons of LNG per day, which is 46 MM m^3 annually.
KRI S.A. based in Wysogotowo close to Poznań	The company has concessions to trade, distribute and import gassy fuel and to liquefy and re-gasify natural gas. KRI SA supplies their customers with natural gas via high pressure pipeline connected to the distribution network and with the use of LNG technology. It also owns an LNG transporting company – PGS Sp. z o.o. It regularly transports LNG to more than ten locations in Poland as well as abroad, e.g. to Sweden. The company also offers LNG emergency deliveries for the time of gas pipeline maintenance or repair works.
G.EN. GAZ ENERGIA S.A. based in Poznań	The company deals with trade and distribution of gas rich in nitrogen and gas rich in methane within 4 Polish voivodships, serving 18000 industrial and public customers as well as individual households. The company has 4 LNG stations in the central part of northern Poland.
KRIO Odolanow - a division of PGNiG.	The company deals with production of the gas rich in methane from gas rich in nitrogen extracted in PGNiG gas mines in Zielona Góra, compression of gas rich in methane and transmission to national network or storage tank, helium recovery, its purification and liquefaction, supply of LNG. LNG produced in Odolanow is a by-product of the nitrogen removal processes from the natural gas. In 2008 PGNiG produced 20,1 MM m^3 of LNG..
LNG – Silesia Sp. z o.o. based in Swierklany	The company deals with implementation and operation of small distributed scale liquefaction systems based on waste and stranded gas resources from coal mines, landfills etc

4.5.4. LNG market potential

LNG may be an attractive fuel alternative due to several reasons, including a competitive price compared to other fuels. The gas distribution network in Poland is not fully developed, and that creates opportunities for LNG producers, as there are many potential industrial and individual customers who could benefit from switching to LNG. A variety of available technologies makes it possible to use LNG in many sectors, both industrial and transportation-related. Another advantage of LNG is its easy use in the case of extreme or emergency situations, during gas shortage or pipeline maintenance works. A more detailed analysis of the transportation sector, especially railway companies, as target market showed that there are several technological solutions available for converting vehicles into

LNG. Some of these solutions proved both economically and technically viable and under certain conditions may bring significant profits.

LNG may be used in the following cases:

a) as gas source before the gas distribution network in a particular area is built;

b) in case of any failure or maintenance work of gas network;

c) as gas source for customers located within areas distant from the transition network, where building a distribution system is economically not viable or impossible due to other reasons,

d) for supplying customers in gas peaks (peak shaving);

e) for fuelling vehicles (with liquefied gas LNG or CNG - Compressed Natural Gas) in LCNG system i.e. conversion of LNG into CNG.

f) for heat and power production.

From the point of view of an LNG producer, the most promising option represents the use of LNG by customers located within areas distant from the transmission network, where building a distribution grid is not cost - effective or possible. Fuelling vehicles with liquefied gas LNG or compressed CNG (Compressed Natural Gas) in LCNG system i.e. conversion of LNG into CNG may become another profitable option in the near future. Other mentioned options do not guarantee stable or long-term sale, but may allow to get higher prices of LNG (especially option b and d).

Polish gas infrastructure is quite well developed, especially in the southern and western parts of the country. However, further development of the gas network, especially for the sake of increasing gas sale, requires high investments, especially in relation to transmission. Geographically, the greatest potential as far as the gas demand is concerned, is in central and northern parts of Poland, however, there are also “white spots” in highly urbanized areas. In Poland, there are 3600 municipalities (875 towns and cities), but the gas is supplied only to 1400 of them (620 towns and cities). Areas without access to the grid constitute 59% of Poland and are inhabited by 23% of the total Poland’s population. As it can be seen, the potential for gas sale, including LNG sale is huge (2200 municipalities). In about 200 municipalities, 590 significant industrial customers were identified as potential LNG buyers while the total natural gas demand was assessed on the level of 1,2 MM m^3. There are many areas where the demand is huge but costs of developing the piping infrastructure exceed the costs of delivering LNG by cisterns. Currently, there is no competition on the Polish LNG market among its actors, however, access to LNG makes a company more and more competitive.

The analysis of the potential LNG end-users from industry sector was based on several basic assumptions: characteristics of reception, consumption structure, seasonality of consumption, end-users characteristics, price competitiveness and distance between end-user and the LNG plant.

Table 9 presents the branches of industry which an LNG producer may be interested in. Replacing the fuels currently used by LNG is feasible in all of them. Each branch differs from the rest and is somehow unique. The table specifies the fuel currently used in a particular industry and its purpose together with the key installations. Potential LNG consumption was calculated for individual branches, however the ranges of demand are quite wide as the consumption depends also on the plant size and type. Where necessary, notes were added to clarify some specifics of a given industry in relation to the fuel supplies.

Table 9. Characteristics of industry sectors – potential LNG users in Poland

Industry sector	Current fuel	Used for	Technology/ equipment description	LNG consumption potential (approximate data)	Comments
Asphalt producers	Heating oil, coal dust, natural gas	Technological processes – heating	Rotary furnaces, driers - heating the asphalt mass	600 ÷ 2.200 tons annually	Production – continuity / security of gas supplies required
Meat industry	Heating oil, coal, natural gas, propane	Technological processes, heating, hot utility water	Technological steam, hot water, smoke – houses	500 ÷ 1.500 tons annually	
Food industry	Heating oil, coal, natural gas, propane	Technological processes, heating, hot utility water	Technological steam, hot water	500 ÷ 1.500 tons annually	
Building and sanitary ceramics	Heating oil, natural gas, propane	Technological processes	Tunnel and pusher furnaces, drying and products firing	500 ÷ 6.000 tons annually (large plants over 10.000 tons annually)	production – continuity / security of gas supplies required
Calcareous industry	Heating oil, coal, natural gas, propane	Technological processes	Rotary furnaces – roasting	1.000 ÷ 10.000 tons annually	production – continuity / security of gas supplies required
Heat engineering	Heating oil, coal, natural gas, propane	Heating, hot utility water	Boilers: hot water, steam	400 ÷ 7.500 tons annually	Different demand for gas within different periods of time during the year
Paper industry	Heating oil, coal, natural gas, propane	technological processes, drying	Steam boilers	750 ÷ 3.800 tons annually	production – continuity / security of gas supplies required

Steel industry (glass works)	Natural gas, propane	technological processes – chemical and thermal	Metallurgical furnace, tank furnaces, melting components in high temperatures	2.000 ÷ 15.000 tons annually	Production – continuity / security of gas supplies required. Process temperature about 1500℃
Insulation manufacturing plants – glass wool	Natural gas, propane, heating oil	technological processes – mechanical and thermal	Furnaces, melting of raw materials and defibering	2.000 ÷ 15.000 tons annually	Production – continuity / security of gas supplies required. Process temperature over 1000℃

4.5.5. Potential position of LNG on gas/methane fuelled vehicles market

A separate segment of the potential LNG end-users market is the so called Natural Gas Vehicles market (NGV). The development of the gas/methane fuelled vehicles market is very dynamic worldwide, yet not that intensively in Poland. However, taking into consideration restrictive emission standards for emissions of car fumes defined by European Union, the development of that particular segment is expected to occur sooner than later.

A serious barrier for the segment development is the infrastructure necessary for the use of LNG as vehicle fuel which is rather poorly developed in Poland. There are only 30 CNG stations (Compressed Natural Gas) compared to about 6,8 thousand petrol stations and similar number of LPG stations (Poland is a world leader in using LPG in vehicles). A promising chance for that segment are the so called LCNG stations providing both compressed natural gas and liquefied LNG, while being also independent from the gas network as for the station location. However, in the present situation individual users of vehicles cannot be considered as a target group. Therefore, the focus seems to be specific transportation companies which may be interested to change their fleets into NGVs. In the first instance it refers especially to such potential end-users as: municipal transport fleets, utility vehicles and heavy road transport as well as rail transport.

Technologically, in both cases, it is possible to apply LNG in two ways: using the engine fully supplied with LNG or applying a conversion system, which allows for a partial replacement of the diesel oil with natural gas/methane. The second solution has a significant advantage for industrial end-users currently using heating oil in the case of LNG shortage, the systems can be easily switched back to diesel oil. Commercially available systems for locomotives' conversion to LNG are delivered by an American company – *Energy Conversions Inc*. With respect to the road transport vehicles, attempts were undertaken by several companies, both in Europe and in the US including some of the main trucks and heavy duty engines manufacturers. The first Polish investment in the bus fleet fuelled with LNG is SOLBUS company, who won public procurement bid for delivery of a fleet of 30 LNG fuelled buses for the municipal transportation company in Krakow in August 2009. It is going to be the first investment of this kind in Poland. Its success will develop a new market of potential LNG off-takers.

The implementation of the Directive of the European Parliament and Council No 2009/33/EC dated 23 April 2009 on the promotion of clean and energy-efficient road transport vehicles will result in a steadily growing interest in using buses fuelled with natural gas. Following the provisions of Article 1 of the Directive when purchasing road transport vehicles the contracting authorities, contracting entities as well as certain operators are required to take into account the lifetime energy and environmental impacts, including energy consumption and emissions of CO_2 and of certain pollutants.

Tests of LNG application as locomotive fuel were successfully conducted in the US. The technology can be applied for long distance rail transport, which is the situation very common in the United States – hauling huge quantities of any commodity for very long distances. The other option is to use LNG as a fuel for shunting locomotives, traveling short distances and frequently operating within the area of a particular factory, e.g. in a coal mine to transport the coal. In both cases one of the major issues to be solved is the LNG storage on the locomotive. In case of long distance rail transport, there is no other option than to use a separate carriage with a storage tank of a huge capacity. For shunting locomotives, two solutions can be applied: a separate carriage, or replacing the diesel storage tanks with LNG storage tanks. Nevertheless, there are a number of other factors which should be considered in the case of locomotives modernization for LNG fuelling. They are presented and discussed in section 4.6.1. of this report.

4.6. Case study of LNG applications in Poland and assessment of their environmental effects

The analysis of the Polish LNG market described in the previous section provided a background for more detailed study of a specific business entity. The first analyzed option was to examine the technical aspects and profitability of the modernization of a T448 P diesel locomotive with the aim to adapt the engine to fuelling with LNG. The second analysis was devoted to LNG application for energy production purposes in a municipal heating boiler installation selected as an example.

4.6.1. Case study: application of LNG as a locomotive fuel

The case study was developed for a locomotive owned by PCC Rail Rybnik S.A The Company owns a railstock of 40 locomotives T448 P type, that was selected as the subject for potential application of LNG as the locomotive fuel. The locomotive T448 P type is presented on Figure 30 .

Figure 30. T448 P diesel locomotive to be adopted to fuelling with LNG

The Company manages rail infrastructure with the total length of the used railways of 241,22 km and owns 1300 train carriages of all types and 89 diesel locomotives for heavy maneuvering works and hauling trains. Majority of carriages are self dumping with heavy loading capacity. The Company owns 3 types of locomotives: T 448 P, S 200 series and TEM 2 series. There are state-of-the-art back up facilities and proper equipment for maintaining and modernization of railway rolling stock and railway lines in the Company.

Currently, all locomotives used in the Company are diesel fuelled. It was assumed that replacement of diesel with the natural gas of LNG origin will decrease the negative environmental effects and simultaneously result in a reduction or even elimination of emission fees related to the operation of the locomotives. The considered factors determining the profitability of the investment include: gas price, modernization costs, the costs of the storage infrastructure built into the locomotive and development and operation of the fuelling system.

Technical conditioning

The following general presumptions were considered in the analysis:

1/ LNG fuelling systems for locomotive can be selected from 3 possible options:

- ***single-fuel*** - when the only fuel burnt is natural gas; modernization will require an alternation of the fuel system or a total replacement of the entire engine by the unit manufactured for being fuelled only with gas,
- ***bi-fuel system*** - where diesel and natural gas are interchangeably used. No co-firing takes place in this system. In case of diesel engines there is a necessity of modernization of the ignition system for the sake of gaseous fuel, and specifically for the sake of ignition,
- ***dual-fuel system*** - where co-combustion of diesel and gas takes place.

2/. At the presently used engines, the natural gas in the liquefied form is never directly delivered to the engine but is first vaporized in a heat exchanger (vaporizer) using the heat from the engine's cooling system. As a warmed up gas, the fuel gets via a mixing mechanism or an injection system to the suction manifold or directly to the cylinder.

3/. An essential parameter in the process of the diesel combustion in engines is the cetane index. For gaseous fuels, the so called methane index is determined. The methane index characterizes the knock resistance of a gaseous fuel. The higher the methane index, the greater the knock resistance of the fuel. Methane index is lower when the concentration of hydrocarbons other than methane increases, and increases with a higher concentration of CO_2 and N_2. A low methane index requires reduction of the compression ratio in engines in order to avoid knocking.

4/. Fuelling engine with LNG requires a cryogenic storage tank, and thus finding a place in the locomotive's construction for its installation. In the case of locomotives fuelled only with natural gas, it is less problematic compared to the dual-fuel locomotives, where there is a need to store both diesel and gas in a liquefied form. A solution to this problem could be installation of the tank with necessary equipment on a railcar located behind the locomotive. This solution is applied for long-distance locomotives. In the case of shunting locomotives (this type was subject of the analysis) the solution with rear positioning of the tank may cause traction-related problems and thus cannot be applied.

5/. To ensure the low temperature of gas storage, the cryogenic tank must be effectively insulated from the ambience. Such insulation may be achieved by placing a pressure tank in an outer vessel with vacuum conditions in the space between the vessels. Moreover, other insulating materials e.g. pearlite must be applied . When filling the tank with liquefied natural gas, 10% of the space must be retained for the left gas, as the vaporizing gas in the tank increases the pressure inside. Daily vaporization ratio in a tank is about 0,45% in the case of the a small tank and about 0,11% in the case of larger ones.

In tanks with pressure higher than the atmospheric pressure, the flow of the fuel is driven by the fuel’s pressure and there is no need to install a cryogenic pump to force the liquid gas to the heat exchanger (vaporizer). Cold gas is heated under the pressure and is vaporized in the heat exchanger supplied with heat coming from the engine’s cooling system. The gas pressure increases in the heat exchanger. After the gas leaves the heat exchanger, it is transferred to the engine. The proper pressure of gas transferred to the engine is indirectly exerted by a pressure valve installed in the tank.

6/. A typical LNG station comprises a storage tank, unloading terminal and a cryogenic pump with fuelling hoses. Such a station may fuel vehicles and devices equipped with LNG cryogenic tanks. An interesting and commonly used solution, which is an alternative to the abovementioned options, is a LCNG [Liquefied Compressed Natural Gas] station. LCNG station enable fuelling both: gas in liquid form and convert liquid gas into CNG with the use of additional devices.

The distribution of LNG may take place independently from gas transmission lines. LNG may be delivered by cisterns to local refueling stations, where it may be stored in cryogenic tanks and sold to vehicles, partly as LNG and partly CNG after vaporization in LCNG stations.

7/. Basic parameters of the T 448 P locomotive:

- a four-axle locomotive with two rotable carts. Four wheeled driving sets are individually driven by four traction engines of a tram-car type. The frame of the locomotive is placed on the carts indirectly using eight elastic elements. The traction force is transmitted from the carts to the locomotive’s frame by king-pins enabling also a lateral move. Secondary cells are located in the rear bonnet behind the machine operator cabin, which is placed over the back cart,
- the auxiliaries are mechanically driven directly from the combustion engine. Water cooling is a two cycle system. A source of the compressed air for the pneumatic brake and all devices pneumatically controlled is K3lok1 compressor,
- equipped a driving unit: a combustion engine CKD type K 6S 230 DR of 883 kW power, connected directly to the traction generator CKD type TD 805 as a one assembly unit, electrical transmission for heavy shunting and maneuvers on tracks of the standard clearance with a maximum speed of 70 km/h,
- operational weight: 72000 kg
- fuel weight: 3300 kg
- amount of engine oil: 485 kg
- maximum load on the wheel sets: 180 kN

- fuel tank:	4000 l

On the bases of the performed analysis, considering the above presented presumptions the following general conclusions were drawn: (i)from the technical point of view conversion of diesel railway stock into LNG is viable, (ii)there are companies in the US which deals in such projects, (iii)a dual fuel system (co-firing of diesel and gas) should be implemented as a cost effective and affordable what means that (vi)converting diesel engines into diesel-natural gas engines is necessary what (vii)does not require changing the entire engine.

Economic analysis

Apart from technical presumptions, economic analysis was carried out to determine if the investment of converting locomotives into LNG fuelled is economically viable. The viability determinants include internal rate of return (IRR) and the net present value (NPV). The investment is economically viable when NPV exceeds 0 with use of an established discount rate which reflects the assumed weighted average cost of capital (WACC) and at the same time when the Internal Rate of Return (IRR) of the project exceeds the assumed WACC.

Input data:

The following breakout of costs was adopted for calculating modernization costs of a single locomotive (Capex):

Fittings	59 500	USD
Pressure reduction, piping, connectors	31 050	USD
Technical support	42 500	USD
Tanks (2 pieces)	20 000	USD
TOTAL:	153 050	USD = 418852 PLN

Costs may be lowered if at least 10 locomotives are modernized at a time. In the case of such an order, the unitary price can be reduced by 25% i.e. US$ 114 788 (PLN 314 139) per unit, a total cost of US$ 1 147 880 (PLN 3 141 390) for 10 locomotives. In this case, the **lower capex is PLN 314 139 per locomotive.**

CPI = 3,00% (in 1st year)
CPI = 2,50% (2nd year)
CPI = 2,00% (from 3rd year)

Structure of financing:

– own capital (equity)	20%
– investment loan	40%
– grant(s)/ financial assistance	40%

Cost of capital:

– own capital	25%
– investment loan	8%
– grant	0%

Income tax in Poland = 19%

Assumed unit prices and energy coefficients were as follows:

Diesel price	2,99	PLN/liter
Diesel consumption	47850	Liters / (pcs x year)
LNG price	1,60	PLN/Nm^3
Diesel density	0,84	Mg/m^3
Diesel calorific value	43,20	MJ/kg
Gas from LNG calorific value	35,00	MJ/Nm^3
LNG targeted consumption (in energy)	60%	---
Savings on operating expenses of the locomotives	5%	---
Locomotive modernization amortization	10%	---

Annual operational costs of an individual locomotive before conversion (Opex prior to conversion)

Description	value (PLN)
Diesel consumption costs	143 071,5
Emission fees	1 214,4
O&M costs	105 928,5
Total:	250 214,4 = 250 214

Annual operation costs of a single locomotive after conversion (Opex after conversion)

Description	value (PLN)
Diesel consumption costs	57 228,6
LNG consumption costs (gas)	47 626,5
Emission fees	1 214,4
O&M costs	100 632,1
Total:	206 701,6 = 206 702

The analysis was performed taking into consideration three scenarios. All these scenarios referred to the modernization costs of a single locomotive. If 10 or more locomotives are upgraded, the investment costs and NPV appearing in the scenarios were multiplied by the number of upgraded systems. Keeping the analytical assumptions, IRR remains the same, independently of the number of upgraded locomotives. The following scenarios were considered in the analysis:

Scenario 1: (base) was used to calculate the level of investment profitability while converting a single locomotive, assuming at the same time that all income and cost factors in future are subject only to inflation correction.

The derivative of this scenario was the scenario 1A assuming conversion of 10 locomotives at the same time.

Scenario 2: assumed that the annual increase in diesel price shall be higher than the inflation rate. The basis for such an assumption was the analysis of Brent crude oil barrel price within last 20 years confronted with the CPI coefficient noted at the same time in USA.

Scenario 3: assumed that LNG price would be indexed using the same rate as the energy unit price from diesel. The consequence of this is a fixed relative price of energy costs from LNG towards the costs of diesel, i.e. the initial factor of 55% would be maintained (see Scenario 2) throughout the entire projection period.

The data below presents results of an economic analysis.

Years	**0**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
Discounted Cash Flow increasingly, PLN											
Scenario 1	-372 167	-327 935	-286 094	-246 883	-210 173	-175 546	-142 924	-112 223	-83 588	-56 484	-31 056
Scenario 1A	-269 444	-227 050	-186 909	-149 269	-114 010	-80 725	-49 342	-19 788	7 788	33 913	58 437
Scenario 2	-269 444	-225 615	-182 640	-140 504	-99 339	-59 249	-20 320	17 386	53 821	88 952	122 759
Scenario 3	-269 444	-226 418	-185 082	-145 443	-107 482	-71 169	-36 472	-3 354	28 228	58 317	86 958

	NPV	**IRR**	**DPB**
Scenario 1	**-31 056 PLN**	**6,35%**	**> 10 years**
Scenario 1A	**58 437 PLN**	**12,68%**	**8 years**
Scenario 2	**122 759 PLN**	**16,71%**	**7 years**
Scenario 3	**86 958 PLN**	**14,56%**	**8 years**
NPV – Net Present Value, IRR – Internal Rate of Return, DPB – Discounted Pay Back			

Results of the scenarios analysis (referring to the assessment of the financial effects) can be concluded as follows:

Conversion of a single locomotive partially into LNG under the current market conditions is not profitable (scenario 1). It may be justified only for the purposes of an R&D activity.

If at least 10 locomotives are converted simultaneously, the capital expenditures unit (capex) decreases significantly. Such investment becomes profitable (scenario 1A), however the profitability indexes remain relatively low.

If fuel prices increase and exceed the consumer price index (cpi) increase, the analyzed investment becomes far more financially attractive (scenarios 2 and 3).

Generally, if the company is exclusively benefit-oriented and does not lead R&D activities, at least 10 locomotives should be selected for conversion and the capital expenditures should be covered using maximum low-cost external capital. Additionally, all possibilities of obtaining grants should be carefully looked into in order to lower the cost of the invested capital.

The environmental effects resulted from replacing diesel oil by LNG as fuel for T448 P locomotives were also determined. Due to technical reasons, a complete elimination of diesel oil appeared impossible, only a 60% replacement by LNG turned out to be a feasible option.

Environmental impact analysis

The assessment of the environmental effect consisted in comparison of pollutants emissions to the air according to the following two fueling scenarios of a locomotive:

- Option 1 – the locomotive uses diesel fuel only
- Option 2 – the locomotive uses a dual fuel system composed of 40% of diesel oil and 60% LNG

The comparison of the air emission effects was carried out in a way described as follows. Pollutants emission was calculated taking into account relevant the air emission factors for diesel locomotives and assuming an average fuel consumption on the level of 40,2 Mg/year (for option 1), and for scenario 2 the dual fuel system with 60% of LNG contribution was considered.

The levels of air pollutants emission reduction achieved due to full diesel replacement by LNG were as follows:

nitrogen oxides NO_x	50 %
sulfur dioxide SO_2	99 %
particulate matter PM10	95 %
carbon dioxide CO2	10 %
cadmium	100 %

For individual options the following reductions of the pollutant emission load could be achieved:

- **Option 1 (diesel fuel only)**

nitrogen oxides NO_x	2171 kg/year
sulfur dioxide SO_2	88 kg/year
particulate matter PM10	189 kg/year
carbon monoxide CO	1186 kg/year
carbon dioxide CO2	127434 kg/year
NMVOC	511 kg/year
cadmium	0,084 kg/year

- **Option 2 (dual fuel system: 40% diesel+ 60% LNG) -**

nitrogen oxides NO_x	1520 kg/year
sulfur dioxide SO_2	36 kg/year
particulate matter PM10	81 kg/year
carbon monoxide CO	1186 kg/year
carbon dioxide CO2	19788 kg/year
NMVOC	511 kg/year
cadmium	0,034 kg/year

The comparison of the emission load to the air for both analyzed fueling options of the T448 P locomotive's engine shows that application of a dual fuel system (option 2) will allow achieving an environmental effect in the form of avoided emission of 7,6 Mg of carbon dioxide, 0,7 Mg of nitrogen oxides, 0,1 Mg of particulate matter PM10 and 0,05 Mg of sulfur dioxide. In the case when a larger number of locomotives are modernized, the environmental effects will be multiplied respectively.

4.6.2. Application of LNG as a fuel for a municipal heating boiler installation

Application of LNG produced from the methane resources originating from the Zory mine in power industry was also analyzed as an alternative targeted market mainly from the viewpoint of the significant environmental benefits it may generate.

LNG could be used either for heat or electric energy production or in a combined process. LNG application for energy production purposes is especially recommended in areas under special protection due to natural qualities (e.g. national parks). Emissions of pollutants from fuel combustion depend primarily on their content in the fuel. The energy carrier in CMM is methane, which does not generate any dust or solid waste during combustion. Moreover, the use of methane as fuel allows eliminating nearly the entire emission of SO_2 and aromatic hydrocarbons.

The comparison of environmental effects of LNG application and other conventional energy carriers was made for small (1-50 MW) and medium(50-300 MW) municipal energy sources. The comparison included emissions of SO_2, NO_2, CO, NMVOC, PM10, cadmium, mercury, nickel, lead, PCDDs/Fs and benzo-a-pirene generated by LNG, hard coal, fuel oil and wood used as fuel in energy production installations. Referred to the unit of produced energy, the emission comparison proved the beneficial environmental properties of LNG (natural gas), especially when compared to hard coal. Moreover, the emissions from the processes of natural gas combustion were the lowest for all pollutants compared to the analyzed solid and liquid fuels. This fact strongly justifies the application of methane as energy carrier, particularly in the cases when flue gas desulphurization and management of solid waste are rendered difficult.

The example below presents the potential environmental effects of using LNG instead of hard coal in a municipal heating boiler installation of 116 MW_t rating power. Heating plants of corresponding or similar capacity are most frequently used for heat generation for municipal purposes in Poland.

In the first step of the analysis, the consumption of hard coal and LNG per time unit (1 hour) was assessed as the basis for emission calculation. Then, using relevant emission factor (EF) values for combustion process of natural gas and hard coal (EF characteristic for boilers used in municipal sector), the difference between emissions from combustion of the two fuels was calculated. The following average performance values of gas and coal fired boilers were used for the calculations:

- hard coal – 522 GJ/h - when the conversion efficiency was 80%
- LNG - 443 GJ/h – when the conversion efficiency was 94%

Results of the performed analysis of environmental effects of LNG application in a municipal heating boiler of 116 MW_t are presented in Table 10.

Table 10. *Environmental effects of LNG application in a municipal heating boiler installation of 116* MW_t

Pollutant	**EF[1] unit**	**EF[1] hard coal**	**EF[1] LNG**	**Emission from coal [g/h]**	**Emission from LNG [g/h]**	**Emission reduction LNG vs coal**	**Annual emission reduction(*), [kg/a]**
1	2	3	4	5	6	7	8
SO_2	g/GJ	900	0.5	130500	61.5	99.95%	260877

NO_2	g/GJ	180	70	26100	8610	67.01%	34980
CO	g/GJ	200	20	29000	2460	91.52%	53080
NMVOC	g/GJ	20	2	2900	246	91.52%	5308
PM10	g/GJ	60	0	8700	0	100.00%	17400
cadmium	mg/GJ	1	0	0.145	0	100.00%	0.29
mercury	mg/GJ	10	0	1.45	0	100.00%	2.9
nickel	mg/GJ	10	0	1.45	0	100.00%	2.9
lead	mg/GJ	100	0	14.5	0	100.00%	29
PCDDs/Fs	ng I-Teq/GJ	100	2	0.0145	0.000246	98.30%	0.028508
benzo-a-pirene	mg/GJ	13	0	1.885	0	100.00%	3.77

(1) – emission factor

(*) - operation time 4000 h/a with average load of 50% of the nominal power

The performed analysis shows that the application of LNG compared to coal combustion in a municipal heating boiler installation of the nominal power of 116 MWt allows to eliminate emission to the air of PM10, cadmium, mercury, nickel, lead and benzo-a-pirene as well as achieve substantial emission reduction of the other considered pollutants (see column 7 in Table 10). The percent of the emission reduction (column 7), recalculated into annual load of the pollutants emitted to the air (column 8), results in the following reduction of emission loads to the atmosphere:

- sulfur dioxide – 261 Mg,
- nitrogen oxides (calculated to nitrogen dioxide) – 35 Mg,
- carbon monoxide – 53 Mg,
- NMVOC – 5 Mg,
- PM10 – up to 17 Mg.

5. Final conclusions

The project proved that the methane resources, in the amount of over 150 mln m^3 which can be recovered from the area of the abandoned Zory coal mine, represent a promising potential for extraction and conversion to LNG in a way which is technically feasible and economically viable in the near future.

Investigations of the optimal method of methane capture, that would be feasible and ensure a continuous easy access to gas resources from areas of the highest methane bearing capacity, led to the construction of the exploratory borehole to the depth of 215 m below the ground level.

The results of the test methane captures and the obtained gas parameters allowed to categorize the CMM as a good quality gas. The boundary parameters for considering CMM conversion to LNG include the minimum methane content in CMM in the range of 50-70% and maximum oxygen content below 8%. High oxygen content requires application of a catalytic reactor in which methane is combusted at the presence of oxygen and as a result carbon dioxide and water are produced. These products must be removed from the process. Therefore, such a situation has a negative impact on the system performance and its economic effectiveness.

The average concentration of CH_4, CO_2, O_2 and N_2 that can be considered as reference concentrations for the Zory CMM were as follows: methane – 80%, carbon dioxide – 1.8%, oxygen – 0.5% and nitrogen – 17%. The determined average concentrations of some trace components did not represent values which could pose serious technological problems at the stage of CMM purification and liquefaction, and were as follows: ethane – 0.012%, propane - 0.01%, C6+ - 0.09%, hydrogen sulfide - 0.059 mg/m^3_n, organic sulfur - 0.406 mg/m^3_n, sulfur total - 0.461 mg/m^3_n, mercury - 2.0 – 18.6 ± 2.4 ng/ m^3_n. Sulfur, mercury and moisture content were much below the acceptable values for pipeline gas. Heat of combustion, Wobbe index and heating value were high enough to classify this gas as a low quality pipeline gas. Only oxygen content exceeded acceptable limit (0.2%), these attributes indicate that the captured gas should be easy to purify and liquefy. Therefore, installation for LNG production may be simple, relatively cheap and economically viable to produce alternative fuel for small scale. Trace components (especially sulfur and mercury) can be removed on small activated carbon bed. Also, power requirements for whole facility may be at reasonable level, independent of implemented refrigeration method.

The balance of the methane resources recoverable from the area of the abandoned Żory coal mine showed that from the total resources estimated initially on the level of 7 777,75 mln m^3, only the deposits located at the depth range of 400-705 m b.g.l, amounting to over 150 mln m^3 can be recovered in a technically viable and economically efficient way within a near-time perspective. However, the quality and the amount of the obtainable methane seem sufficient to make a positive decision on a profitable investment. In recovering methane from sealed mines it is of critical importance to carefully balance the withdrawal rate with the natural recharge rate. If wrong, water encroachment for example would accelerate and air could be drawn into the gob reducing the gas quality.

The entire process of the Zory methane capture, conversion to LNG including the borehole drilling phase, gas extraction, its purification and liquefaction and finally application at a targeted market were analyzed in details and assessed from the viewpoint of the potential negative effects on the environment as well as environmental benefits.

The drilling of the borehole turned out to be relatively safe for the environment. Some negative effects were identified, such as pollutants emission to the air generated by the work of the diesel engine of the rig and the flushing pump as well as at the stage of the test gas capture (flare). Some emissions to the air may also appear during gas extraction from the borehole, mainly due to gas discharge during testing or siphoning of the borehole, functioning of the safety valves preventing excessive gas pressure, gas escapes through leakages in the pipes and equipment, etc. Noise emission was also identified as a negative environmental effect of the drilling works. However, it should be stressed that none of the identified impacts related to the borehole drilling and methane extraction is of persistent character, as they occurred only over a very limited period of time. The exceeded standards of nitrogen oxides emission were observed only during the performance of the drilling works.

Potential impacts on the environment were also analyzed in the case of the CMM purification and liquefaction technologies, taking into account their applicability to process the recoverable gas resources from the abandoned Zory coal mine. It was found that the environmental noxiousness of the methods of the CMM dehydrating depends primarily on the composition of the raw gas, e.g. the content of benzene, ethylene, toluene and xylene as well as on the size of the installation. That is why the final decision on the selection of the most environmentally appropriate drying method depends primarily on the technological issues. Adsorption on molecular sieves proved the least burdensome for the environment among the considered methods of CMM dehydration. The methods of acid gas removal were assessed as posing no particular environmental risks. The least amount of contaminants is discharged to the environment from the method based on adsorption using molecular sieves. Since the mercury content in the CMM obtained from the Zory site was small (below 0,001 mg/Nm^3), its removal would not be necessary for CMM conversion to LNG and no negative mercury impact on the environment at the stage of CMM purification should be expected.

The results of analysis of the liquefaction methods showed that they are non-emission technologies from the viewpoint of emission to the air, water and soil (streams of generated waste). The exception is noise emission, due to the need of applying compressors and/or turboexpanders in the installations. This equipment may cause exceedances of permissible noise emission levels for areas where these standards are more restrictive, e.g. residential areas. Due to the fact that the Zory site is located in a relatively short distance from a residential area, the environmental impact assessment report should be carried out at the design phase of the LNG installation to identify if the permissible noise emission standards are exceeded. If exceedances are stated, special acoustic screens must be installed.

In order to identify the economic and technical issues as a background for potential investment opportunities, the most promising applications of LNG from the Zory borehole were analyzed together with a broad analysis of the Polish gas market. The study showed the LNG market is a niche segment of the Poland's highly monopolized gas market, with several key players. Yet it represents a promising potential, due to number of reasons such as competitive price of LNG compared to other fuels, the fact that the gas distribution network is not fully developed in Poland and the applicability of LNG as an alternative fuel in transportation sector supported by favorable legal regulations as well as a number of other industries in which LNG can successfully replace the conventional energy carriers. A separate segment of the potential LNG end-users market is the so called Natural Gas Vehicles market (NGV). The development of the gas/methane fueled vehicles market is very dynamic worldwide, yet not that intensively in Poland. However, taking into consideration restrictive emission standards for emissions of car fumes defined by European Union, the development of that particular segment is expected to occur in a near term perspective.

The analyses showed that in Poland, LNG may be used first of all for the following purposes:

- as gas source before the gas distribution network in a particular area is built;
- in case of any failure or maintenance work of gas network;

- as gas source for customers located within areas distant from the transition network, where building a distribution system is economically not viable or impossible due to other reasons,
- for supplying customers in gas peaks (peak shaving);
- as fuel or semi product in the following branches: ceramic industry (bricks, tiles, etc.), steel, grocery, heating, glass works, chemical industry, lime industry, asphalt plants, food producers
- for heat and energy production
- for fuelling vehicles with liquefied gas LNG or CNG (Compressed Natural Gas) in LCNG system i.e. conversion of LNG into CNG. This refers in particular to municipal transport fleets, utility vehicles, heavy road transport and rail transport.

A detailed case study performed within the project focused on the last two applications of LNG, taking into account the general conditions of the Polish gas market as well as the potential local market end-users. The first analyzed option was to examine the technical aspects and profitability of the modernization of a T448 P diesel locomotive, with the aim to adapt the engine to fuelling with LNG. The second study was devoted to LNG application for energy production purposes in a municipal heating boiler installation selected as an example. This application was considered from the viewpoint of the significant environmental outputs it may generate.

Results of the analysis of potential LNG application as a locomotive fuel showed that conversion of a single locomotive partially into LNG under the current market conditions is not profitable. It may be justified only for the purposes of an R&D activity. Generally, if a company is exclusively profit-oriented and does not lead any R&D efforts, at least 10 locomotives should be selected for conversion and the capital expenditures should be covered using maximum low-cost external capital. For 10 locomotives converted simultaneously, the unit capex decreases significantly. Such investment becomes profitable, however the profitability indexes remain relatively low. If the fuel prices increase and exceed the cpi-indexed increase, the analyzed investment becomes far more financially attractive.

From the technical and environmental viewpoint, LNG can successfully replace conventional fuels (in particular hard coal) in separate or combined processes of heat and electric energy production in small and medium municipal installations. This application of LNG represents high potential, particularly in areas under special protection due to natural qualities, nature conservation (e.g. national parks) or health resorts.

Methane recovery from the abandoned Zory coal mine will result in signifficant environmental benefits. It will cause a negative pressure in the void space of the abandoned mine which practically eliminates the up-to-date uncontrolled gas emission through the shafts and conduits and thus reduces the greenhouse effect. Only the CMM capturing will help avoiding methane emission due to its release from the rock mass distorted during mine operation. The volume of this emission varies in time e.g. for the year 2009 it amounted to ca 490,000 m^3CH_4 per year (351 Mg CH_4/year), which recalculated to CO_2 emission is an equivalent of 7.371 Mg of CO_2 emitted yearly. This effect can be leveraged by the application of LNG as a clean, alternative fuel. The replacement of diesel oil by LNG as fuel for T448P in the most feasible dual-fuel system (60% LNG, 40% diesel) will allow achieving an environmental effect in the form of avoided emission of 7.6 Mg of carbon dioxide, 0.7 Mg of nitrogen oxides, 0.1 Mg of particulate matter PM10 and 0.05 Mg of sulfur dioxide. In the case when a larger number of locomotives are modernized, the environmental effects will multiply respectively.

Analysis of the environmental effects of replacing conventional fuels, especially hard coal by LNG in a medium municipal heating boiler installation proved the benefits of methane application as energy carrier. When combusted, LNG does not generate any dust or solid waste. Moreover, compared to hard coal, the use of LNG fuel allows eliminating nearly the entire emission of $SO_{2,}$ heavy metals, aromatic hydrocarbons, reduce the emissions of NO_2 by 67%, as well as CO and NMVOC emissions by 91,5%. This fact strongly justifies application of CMM as energy carrier for heat and power production installations particularly in the cases when flue gas desulphurization and management of solid waste are rendered difficult.

The procedure of assessing the avoided emission applied in the Zory coal mine project may find application for assessing the possibly avoided emisions from other abandoned coal mines in Poland. However, such an assessment will be possible only after an inventory of data from the abandoned mines especially referring to the methane operating emission in the last year of their operation and the number of years since their closure.

6. Next steps

The data obtained from the Zory coal mine project proved that the abandoned Zory mine represents a significant resource of recoverable CMM for potential commercial use. Also the data on the quality of CMM, especially the methane content in CMM on the level of

80%, allow to state that the gas is an attractive input raw material for a wide range of market applications.

Nevertheless, one of the major challenges for the utilization of the recovered abandoned coal mine methane (ACMM), even of such high quality as the Żory gas, is the purification or upgrading process and more specifically the removal of the gas-contained components. Efficient processing of the Zory CMM requires removal of CO_2, H_2S, H_2O and other impurities including nitrogen and oxygen. So far no attempt has been made in Poland to purify CMM from abandoned coal mines with the purpose of its final recovery as LNG. A typical use of CMM in Poland is for heat production, CH&P and for electricity generation in gensets. The CMM parameters required for these types of end-uses are less restrictive than for methane compressing, injection into gas pipelines or LNG production, however they impose a limitation of its market applications.

The next steps should therefore aim at demonstrating a promising, costs effective technology for purification (upgrading) of the coal mine methane that is a critical condition for increasing the portfolio of its market applications. Moreover, the obtained results would help determining the potential investment opportunities. The effort will provide new data necessary to assess the costs of the future commercial installations for CMM purification alongside with the market analysis for a product of specific parameters acquired from the demonstrated system. Such project will require technical and financial assistance, in particular finding a partner who could offer a small pilot installation for *in situ* purification and possibly liquefaction of CMM to be installed close to the Żory borehole. This demonstration project will enable the CMM providers from the abandoned coal mine in Poland but also from the Czech Republic (only 40 km from the Zory site) making decisions on similar ways of methane processing. Beside technical advancements of the knowledge of CMM conversion to LNG in the region, the project will provide the potential LNG producers with a set of data on the environmental influences of the LNG purification and production installation. This experience could be shared thanks to the results of the Poland Methane-to-LNG Project.

The key findings of the Poland Methane-to-LNG Project, including the market analysis and the environmental implications indicate that CMM from the abandoned coal mines including Żory represents a promising opportunity from environmental and financial viewpoint in a very short time perspective. Poland's environmental policy resulting from the strategic priorities set up by e.g. climate and energy package, the need to diversify the energy sources and the still unused resources of CMM in the closed down coal mines provide premises to make an attempt of carrying out a theoretical study based on applying the Life Cycle Thinking approach to assess the overall environmental effect of applying

LNG produced from the abandoned coal mines in the identified most promising markets in Poland e.g. transportation sector and energy production sector. Beside environmental data the project will provide information important from the viewpoint of the national energy policy and business planning.

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