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Challenges for Sustainable Development: The Case of Shale Gas Exploitation in Poland

Wyzwania dla rozwoju zrównoważonego: przypadek eksploatacji gazu łupkowego w Polsce

Jakub Siemek*, Stanisław Nagy*, Paweł Siemek**

**AGH University of Science & Technology, Drilling & Oil-Gas Faculty*
Al. Mickiewicza 30, 30-059 Kraków, E-mail: stanislaw.nagy@agh.edu.pl
***Grupa Lotos S.A., ul. Elbląska 135, 80-718 Gdańsk, E-mail:pawel.siemek@grupalotos.pl*

Abstract
In the current century, natural gas has become the most important fossil energy resource and also important energy fuel in general. And these are both due to significant resources, especially of unconventional natural gas, and ease of transport or transmission, use but also the level of carbon dioxide emissions from burning natural gas.
Significant increase in gas consumption, in all regions, will be marked in the energy sector. Northern America and Western and Central Europe consume most of the gas on electricity and heat production. The exploration of unconventional gas reservoirs has been discussed recently in several scientific fields. Technical, organizational and economic challenges related to sustainable exploration, documentation of reserves, exploitation and development of shale gas technology have been addressed in this paper. Activities oriented to acceleration of prospecting and investment activities as well as difficulties with introducing pro-ecological procedures and technical modifications caused by minimization of influence of the drilling and environmental simulation of production wells have been presented. This study explains some ecological aspects of the extraction technology.
The pace of technological development in Poland may be considerably delayed by the new requirements set by geological and mining law, slowing down of exploration works and recognition of most important gaseous horizons. The scope of investments spent on infrastructure for treating, transport and distribution of gas may have an impact on the rate of realizing energy investment. The rate of development of industry will be conditioned by properly defined economic objectives and the feasible development of gaseous energy industry, being an element supporting the classic coal energy, now mainly a regulation of energy sales in peak seasons.
Probable scenarios (based upon business, legal and geological situation) have been discussed.

Key words: sustainable development, sustainable energy, oil shale, gaseous energy industry

Streszczenie
Gaz ziemny jest obecnie jednym z najważniejszych nośników tak energii kopalnej, jak i energii w ogólności. Dzieje się tak z uwagi na powszechną dostępność zasobów, łatwość w jego transportowaniu, a także z uwagi na niski poziom emisji CO_2 podczas spalania tego nośnika energii. Prognozuje się dalszy wzrost wykorzystywania gazu w sektorze energetycznym i to we wszystkich regionach świata. W Ameryce Północnej a także Europie Zachodniej i Wschodniej gaz służy do produkcji energii elektrycznej i cieplnej. Ostatnio coraz częściej na naukowych forach dyskutuje się zagadnienie eksploatacji zasobów gazu niekonwencjonalnego. W tym artykule przedstawiamy uwarunkowania eksploatacji gazu łupkowego w kontekście rozwoju zrównoważonego, prezentując aspekty techniczne, organizacyjne i ekonomiczne odnoszące się do stanu rozpoznania zasobów i ich eksploatacji. Przedstawiono podejmowane działania mające na celu zwiększenie poziomu pozyskiwania gazu łupkowego i problemy związane z wdrażaniem procedur proekologicznych i modyfikacji technicznych, wynikające z

obowiązku minimalizowania wpływu na środowisko procesu wiercenia. Artykuł wyjaśnia także podstawowe aspekty ekologiczne związane ze szczelinowaniem.
W Polsce rozwój tych technologii może ulec ograniczeniu z uwagi na nowe wymagania wynikające z prawa geologicznego i górniczego, spowalniające prace poszukiwawcze i rozpoznawanie zasobów. Niezbędne jest określenie poziomu środków finansowych niezbędnych do tworzenia infrastruktury związanej z pozyskiwaniem, transportem i dystrybucją gazu. Ujmując inaczej, szybkość rozwoju przemysłu gazowego będzie uwarunkowana przez właściwie rozpoznanie uwarunkowań ekonomicznych.
W artykule przedstawiono także prawdopodobne scenariusze na przyszłość, oparte na podstawach biznesowych, prawnych i geologicznych.

Słowa kluczowe: rozwój zrównoważony, zrównoważona energia, gaz łupkowy, energetyka gazowa

Introduction

In this century, natural gas became the most important energy raw mineral and energy fuel both because of its considerable reserves, especially natural gas from unconventional sources, and also easy transport, use and carbon dioxide emission accompanying combustion of carbon dioxide – factors crucial in the context of sustainable energy.
Natural gas is one of the most desired energy carriers in the World, having a higher level of social acceptance than other energy carriers, nuclear energy, in particular.
Considerable increase of gas consumption in all regions will be well seen in the energy sector. North America as well as Western and Central Europe consume most of the gas for electric energy and heat production. The development of gas-energy over the last ten years was caused by (Siemek & Nagy, 2012):

- Introducing on large scale comfortable combined-cycle technologies (CCGT, CHP – associated use of gas and steam turbines or gaseous motors from some kW to 300 MW of turbines).
- Reaching high efficiency of cycles – over 50% (full cycle *electric energy – heat* – about 90%).
- Lower capital and exploitation cost, shorter time of building and start-up, fewer complex designs, simpler constructions and installations as compared to atomic technologies and hydropower plants. However, the unit cost hydrocarbons, i.e. natural gas and oil are higher than that of coal and nuclear fuel, at least in Europe.
- High degree of social acceptance.

Other factors additionally accelerated the development of gas industry in the World, i.e.:

- Development of liquid natural gas (LNG) and its markets.
- Large scale gas from unconventional sources, mainly in the USA.
- Unprecedented craving for long-term gas production, transportation and distribution (energy safety of countries).
- New principles according to which gas industry and gas market are regulated.
- Natural gas – the only primary energy carrier controllable at every link of a gaseous chain stays under strong political influences owing to its transport possibilities.

The world's population in 2030 may exceed 8.2 billion, to increase to about 9 billion in 2050. Energy deliveries to those people at that time can be realized only with a considerable share of recoverable energy carriers, i.e. natural gas, oil and coal. The share of those minerals in the primary energy profile of 2030 will be about 80%. The considerable share of natural gas will be maintained and may even increase over 23-24% according to EIA and IGU predictions (Siemek & Nagy, 2012).

The world's natural gas resources

By the end of late 1990's the natural gas resources have been associated exclusively with conventional resources, where gas was deposited in porous and permeable sandstones or limestones. Such resources may be found at some hundred to some thousand meters of depth (6000-8000); they are usually limited by impermeable layers, underlying layers and water-saturated surrounding layers. This naturally closed geometrical structure formed traps for the migrating gas generated in source rocks. The magnitude of conventional gas resources was described by the International Energy Agency (IEA) as: documented resources and perspective resources. Their magnitude has been illustrated in figures in table 1.
Perspective resources are over 2 times bigger than the resources in well recognized and documented natural gas fields. The World's gas consumption in 2008 was equal to ca. 3 018 billion m^3 (bcm), and this quantity of gas in documented reservoirs would suffice for over 60 years; however perspective reserves considerably elongate this period by over 120 years. Accordingly, this primary energy carrier can be viewed as dominating in the 21st century. It is also important that gas reserves from unconventional gas sources started to be documented.
Those reserves still remain poorly recognized in the World, except the USA; however, the recently assessed resource potential has revealed their significance, mainly due to the fact that they can be explored and documented on a local scale.

Table 1. Distribution of natural gas from conventional sources in various regions of the World, 2008. Source: IEA, 2009.

	Documented resources (tcm)	**Share in World's resources (%)**	**Recoverable resources (tcm)**	**Recoverable so far (tcm)**	**Reservoir leftovers (tcm)**	**Share in World's resources %**
Middle East	75.2	41.2	134.8	2.3	132.5	32.8
Eurasia	54.9	30.1	151.8	15.2	136.5	33.8
Pacific Asia	15.2	8.3	33.9	3.1	30.8	7.6
Africa	14.7	8.1	29.9	1.2	28.7	7.1
North America	9.5	5.2	68.8	36.6	32.2	8.0
Latin America	7.5	4.1	24.5	2.1	22.4	5.5
Europe	5.4	3.0	27	5.7	21.3	5.3
World	182.4	100	470.7	66.1	404.5	100

1 tcm = 10^{12} Sm^3, 1 bcm=10^9 Sm^3, 1 mcm=10^6 Sm^3

Tab. 2 Gas reserves from unconventional sources. Source: IEA, 2009.

Region	**Tight gas**	**Coal-bed methane (CBM)**	**Shale gas**	**Total**
Middle East and North Africa	23	0	72	95
African countries south of Sahara	22	1	8	31
Former USSR	25	112	18	155
Asia – Pacific	51	49	174	274
Middle Asia and China	10	34	100	144
OECD Pacific	20	13	65	99
South Asia	6	1	0	7
Far Asia - Pacific	16	0	9	24
North America	39	85	109	233
Latin America	37	1	60	98
Europe (total)	12	8	16	35
East and Central Europe	2	3	1 (underrated)	7
West Europe	10	4	14	29
World	**210**	**256**	**456**	**921**

1 tcm = 10^{12} m^3, 1bcm =10^9 m^3

Total unconventional gas resources considerably exceed gas resources from conventional sources nearly seven times, with the dominating role of the shale gas in the source rock (tab. 2).

Another evaluation of natural gas resources in unconventional sources has been made by Dong, Holditch et al. (2011) and repeated by Wilson (2012). It is also worth noting that there exists newest correlation between gas from conventional sources and hydrocarbon from unconventional ones, coal including. It shows a simple relation between Original Initial Gas in Place (OIGIP) from conventional and unconventional sources, shale gas including:

$$G_{CBM} = A \cdot G_c \qquad (1)$$

where:

G_{CBM} – OIGIP coal-bed methane,

G_c– OIGIP coal beds.

$$G_{TG} = B \cdot G_g \qquad (2)$$

where:

G_{TG} – OIGIP from low permeable reservoirs (tight gas),

G_g – OIGIP of natural gas from conventional sources.

$$G_{CBM} + G_{NGS} = C \cdot (G_{TG} + G_o + G_g) \qquad (3)$$

where:

G_{NGS} – OIGIP of shale gas,

G_o – original initial oil in conventional reservoirs.

In place resources were calculated with probability calculus method and they were equal to 3590 tcm (P50) of World's natural gas in unconventional resources, i.e. nearly four times more than 1300 tcm (Roger, 1997). The P90 (exploitable) gas from unconventional resources was 2380 tcm. The total initial coal-bed methane resources are P50 231 tcm and P10 (exploitable) 37 tcm. The tight gas resources of P50 and P10 are 2500 tcm and 1400 tcm, respectively. Natural gas from shales is: P50 1420 tcm and P90-943 tcm, respectively. For Europe, the two shale gas category resources are: 63 tcm (P50) and 43 tcm (P90), respectively.

Gas industry development

Another important stimulator of natural gas production is a breaking-through technology of gas exploitation from unconventional sources, successfully implemented in the USA.
That gas production technology, improved over the last decade, is a central reference point for the American economy. Let's quote Dr. Guy Lewis (Gas Technology Institute) in the Wall Street Journal (2009): *Technology of shale gas exploitation looms as the biggest innovation in the energy industry of the decade. Others call this 'revolution'. Regardless the name, these are not new energy sources.* ***The technological novelty lies in the way 'unconventional' gas becomes exploitable locally and globally with the use of advanced technology capable of 'opening' rich energy sources****.*
This quote shows how technological achievements can be perceived from the point of view of civilization changes (local access to gas resources, limiting of CO_2 emission). In the context of a general trend to partially refrain from the planned investment on the nuclear energy industry (or lower the investment rate) or classic coal-based energy industry it gives a clue as to the direction we should be heading, how the energy policy should be changed in the case of confirmed resources or technical and economic production.
Using geological and economic factors jointly as an adaptation of the existing technologies will decide about the development of energy sector in Poland. It cannot develop if the gas exploitation costs remain at a high level. In such a situation one can expect an energy breakthrough both in Poland and in Europe especially that Europe has not been interested in the technological development and is ready to pay a high price for the access to natural gas resources.
The situation looks different in the USA, where the development of production technology completely reversed trends with energy investments, mainly in relation with four times lower gas prices as compared to Europe's standards. The low energy price trends will stimulate the development of the American economy in the coming years, with special emphasis on rapid expansion of the 'energy-consuming' branches, apart from traditionally developed new information technologies.
In the context of hopes for full energy independence from neighbouring countries, we may ask a question of whether the gas madness in the USA over the last years can be implemented in the Europe's conditions, Poland in particular. Did not we have such a rush in the Silesia region in the 1990's when the annual production of coal-bed methane was assessed to 2 billion normal cubic meters? This time the expectations reached a higher level of tens billion cubic meters per year.
The expectations were rapidly chilled down by recent reports by PIG (2012) and USGS (2012). These reports are in a complete opposition to their predecessors EIA (2010), ARI (2009), Wood Mackenzie (2009).
However, it seems that estimations presented in these reports will be verified many times, regardless the fact that each of them was performed on the basis of other assumptions and data. The lack of real exploitation data complicates comparing those reports and reveals shakiness of data used.
Although every adult in Poland is familiar with the technology of shale gas exploitation, and every such person also has his viewpoint shaped by media or such films as, e.g. *Gasland*, it is still worth presenting the most characteristic elements of this technology:

1. Geological characterisation of unconventional resources.
2. Technology of drilling and fracturing.
3. Enhancing gas production, cleaning, processing and transport.
4. Issues related to the minimization of environmental impact.
5. Process economics and possible influence of technology on the sustainable development of country's economy.

Characteristics of shale gas rocks & natural gas from shale's

The origin of hydrocarbons is usually connected with the transformation of organic matter in definite thermodynamic conditions. This view is commonly encountered in modern science, though we should be aware that shallow natural gas resources may be of biogenic (bacterial) origin. Owing to the presence of methane in meteorites one cannot exclude the *inorganic theory of natural gas origin*. Further in the paper the authors will refer to the gas generated in thermogenic processes, among which are oil windows, gas-condensate and oil windows, related to the temperature of the process (and indirectly with depth).
Classic oil and gas reservoirs are mainly connected with the processes of hydrocarbon migration from source rock (where hydrocarbons were generated) to reservoir rocks with perfect or good hydro-mechanical properties (proper permeability and considerable porosity). Such classic reservoirs, deposited in the so-called *structural, lithofacial* or *tectonic traps* significantly differ from unconventional reservoirs. The latter usually has low or ultra-low permeability (usually below 0.1 md (10^{-16} m^2).
There can be distinguished four main types of unconventional gas reservoir (scheme of gas reservoir formation in fig. 1, classification of reservoirs after Halliburton in fig. 2, resources pyramid in fig. 3):

1. Gas in low-permeability reservoirs (from <0.1 to <0.001 md), deposited in pores

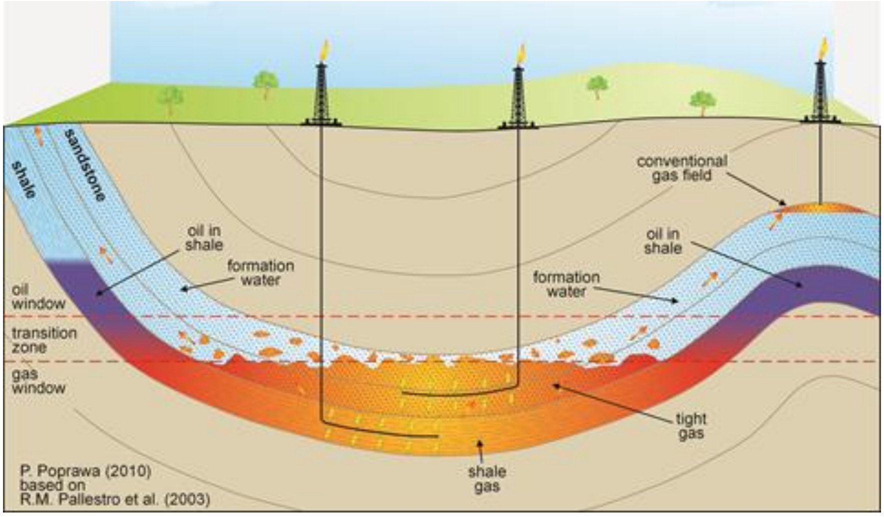

Figure 1. Scheme of natural gas formation in unconventional sources. Source: Poprawa, 2010.

with limited interconnections (*tight gas*).

2. Gas (methane) in coal beds, both as free gas in fractures and adsorbed (*coal-bed methane*).
3. Gas from clayey-mudstone rocks (*shale gas, natural gas from shales* (NGS).
4. Bounded gas in the form of hydrates – no efficient technology for its recovery is available now.

According to another classification, a number of other unconventional gas and oil reservoirs, can be distinguished: shale oil and oil shale, gas fields formed as a consequence of underground gasification, artificial reservoirs related to the biogas generation, natural gas fields in porous structures *permafrost*, reservoirs in very deep structures, gas dissolved in high-pressure hydrated horizons.

Something makes these reservoirs different from the classic ones, i.e. these gases cannot be extracted without additional operations, which artificially change the structure of the rock. Such unconventional gas reservoirs also differ from their classical counterparts in accumulation, as they are **dispersed over a large area** covering considerable geographic regions.

Another distinguishing property is the **necessity of drilling horizontal wells and multilevel fracturing of wells to obtain commercial-scale gas production.**

Among the best known such unconventional reservoirs in Poland are shale gas and coal-bed methane reservoirs, then undiscovered *tight gas* in the Rotliegendes strata in central Poland (Siemek & Nagy, 2012; Nagy & Siemek, 2011).

Organic matter generating hydrocarbons (oil, natural gas) is kerogen (insoluble). The ability to generate hydrocarbons depends on: oxygen to carbon in kerogen ratio as well as hydrogen to carbon ratio. The best properties refer to type-III kerogen, partly type-II kerogen within the *gaseous/gaseous-condensate window*, where natural gas is generated.

When assessing potential resources, there are also evaluated Total Organic Content (TOC) and vitrinite reflectance (the main component of kerogen) $R_{o.}$

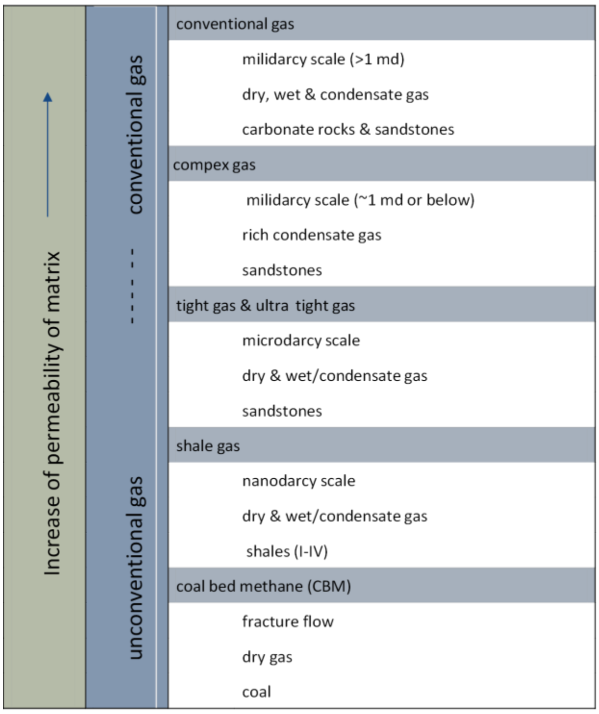

Figure 2. Conventional and unconventional resources. Classification after Halliburton.

It has been assumed that shales containing over 1-2% TOC have enough gas and are exploitable. The best shales may reach up to 12% TOC. Apart from the mentioned properties, it is also other reservoir parameters which are indicated: porosity coefficient >4%, permeability coefficient >100 nanodarcy (>10^{-19} m^2), vitrinite reflectance $R_o > 1.3$-1.5%.

Shale rocks hosting natural gas are typically very thick and regionally extended, with no visibly developed insulating layers and structural traps, no distinct gas-water contour, though water can be present in 75-80% of saturation, a natural system of fractures occurs in the reservoir, though the rock matrix has very low-permeability.

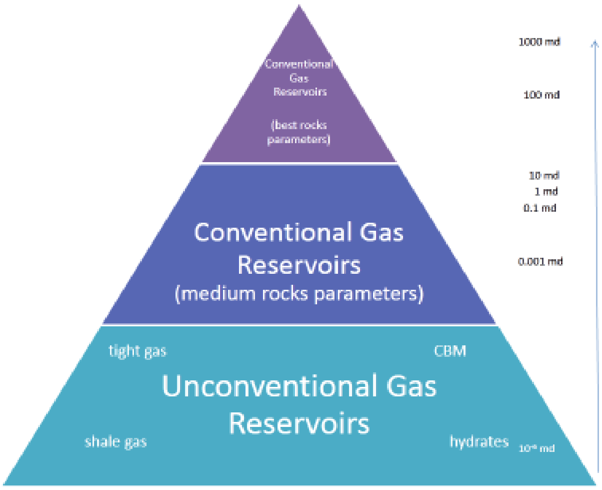

Figure 3. Classic pyramid of unconventional and conventional gas sources. Source: EIA SP, 2011, mod.

Table 3. List of basic parameters typical of selected sedimentary basic. Various sources.

	Poland		
	Baltic Basin	Podlasie Lowland	Lublin Region
Age [million years]	420–445	420–445	420–445
Top [m]	2500–4500	2000–3500	2000–5000
Total thickness [m]	<600	< 120	< 120
TOC [%]	1–4	1.5–6 (<20)	1–3
Ro [%]	1.3 – 2.5	0.8 – 3	0.8 – 5
Kerogen (type)	II	II	II

	USA	
	Barnett	Marcellus
Age [million years]	340	385
Top [m]	2300	2150
Total thickness [m]	90	105
TOC [%]	4.5	3.3
Ro [%]	2	1.3
Kerogen (type)	II	II and III

	Canada
	Horn River
Age [million years]	370
Top [m]	2700
Total thickness [m]	140
TOC [%]	3.0
Ro [%]	2.5
Kerogen (type)	II

Three main basins exist in Poland: Pomerania (Baltic), Podlasie and Lublin basins. Some parameters of selected shale basins in Poland and North America are presented in tab. 3. The characteristic areas where shale resources occur in Poland and Europe are visualized in figs. 4 and 5.

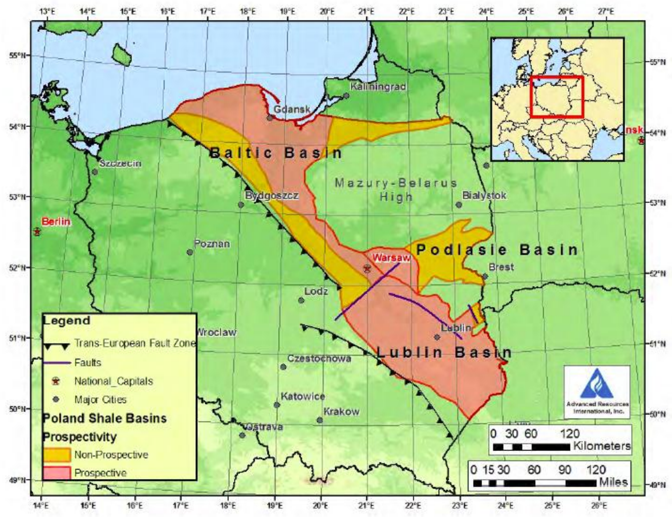

Figure 4. Main areas of gas production from unconventional reservoirs. Source: EIA, 2011.

Advanced drilling technology of horizontal wells

Gas exploitation must be preceded by drilling the wells. By the half of the last decade vertical wells prevailed, though for the last five years mainly horizontal wells have been mostly used. Horizontal wells are drilled perpendicular to the existing network of fractures in the shale deposits. The drilling operations are followed by multistage fracturing. Fracturing operations generate fractures along the well (perpendicular to the horizontal well axis). They increase the surface of contact with shales thus stimulating gas flux. The formed fractures propagate to over 300 m distance from the well (Davies, 2012). The vertical range of penetration usually does not exceed 200 m (up and down from the fractures layer) (Shale Gas Primer, 2009; Davies, 2012).

The environmental issue connected with limiting the space occupied by drilling has been solved since 2007. This is one of the subjects frequently discussed in the press in relation to prior technologies used for gas exploitation of *shallow* shale resources, mainly in Texas and Marcellus Field (Shale Gas Primer, 2009).

The present technologies offer the possibility of drilling up to 32 wells from one site, which is both economic in view of leasing the site, access to the drilling place, rigs, mud circulation systems, fracturing systems, post fracturing cleaning systems, etc. Moreover, the wells can be connected with the collector and transport pipelines faster and cheaper.

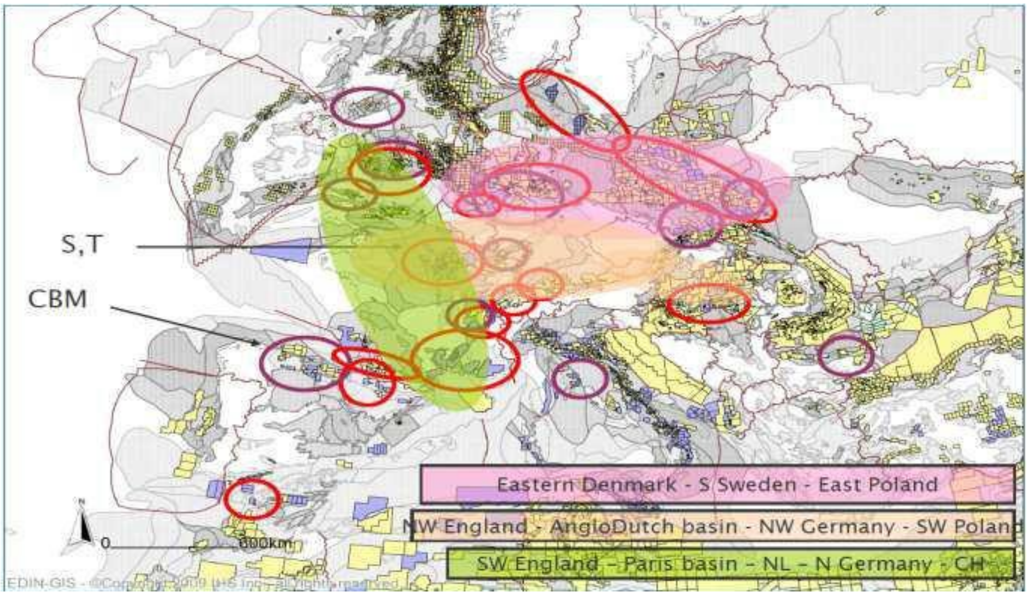

Figure 5. Main basins of shale gas presence in Europe. Source: EDIN-GIS HIS CERA, 2010 after Kuhn & Umbach, 2011.

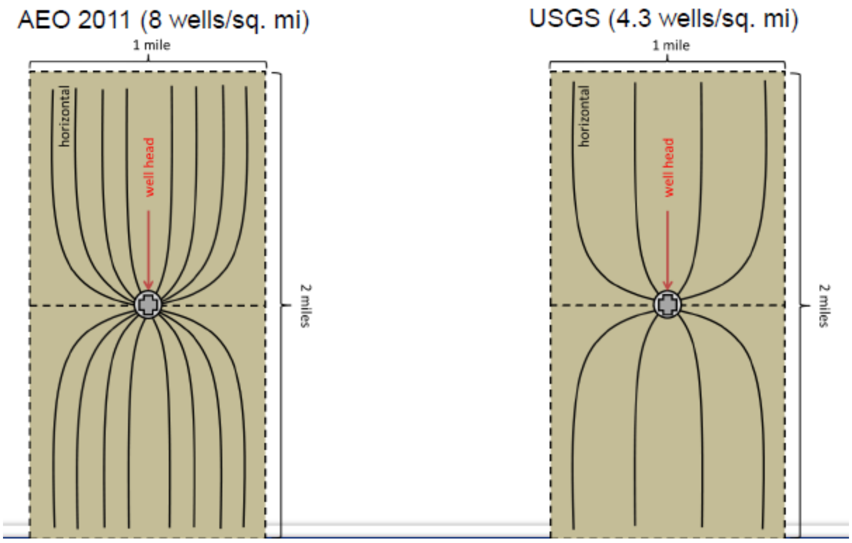

Figure 4. Example of different classification systems of gas production by EIA and USGSS: density of wells. Source: Krupnick, 2012.

Efficiency of hydraulic fracturing

Stimulation of the well increasing low permeability of the reservoir, lies in hydraulic fracturing and the formation of a grid of fractures. A low-viscosity fluid is injected to the well under a high pressure with higher rate that it is expected to flow. The hydraulic resistivity related to the flow in the rock formation increases, the pressure in the well grows above the fracturing pressure making the rock matrix break up and form a fracture or a network of fractures. Most commonly a vertical fracture is formed in two opposite directions, perpendicular to the well axis (Valko, 2009). *Wings* of the fractures are usually symmetrical if the fracturing is performed in the sandstones. In the *shale gas*/CBM reservoirs a system of fractures can be formed in the existing natural tiny fractures.

The important factor stimulating origin of fracture formation is the presence of silica or carbonates in the clayey rocks. The fracture can be protected against its closing by *proppant*. Some literature analysis reveals that the efficiency of the simulation can be increased by another distribution of fractures, formed by orthogonal positioning of natural and artificial fractures. Fracturing od shale gas is usually performed with the use of slickwater-type fracturing fluid (classic fracturing fluids are composed of four types of fluid: water-based, foam, hydrocarbons and recently also propane (LPG) (Shale Gas Primer, 2009; WEO SP, 2012). *Slickwater* covers water with drag reducing agents – substances for the increase of pumping velocity above

9 m^3/min. The pumping rate of such a solution may be even 15 m^3/min. It is assumed in the process that friction is maximally lowered, usually with the use of polyacrylic gels. The biocides, surfactants and inhibitors of mineral precipitation are also elements of slickwater. The biocides fight against living organisms, which may limit the flow. Methanol and naphtalene can be used as biocides. Hydrochloric acid and ethylene glycol can be used as scale inhibitors. Butanol and ethylene glycol, monobutyl ether are used as surfactants. Substitutes of these chemicals also can be used.
All those additives make on the whole about 1% of the slickwater. The present substances are commonly used in households and kitchen (*green additives*).

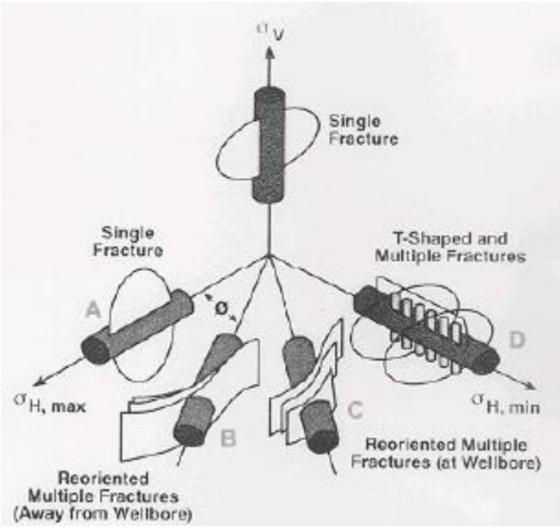

Figure 5a. Formation of fractures in vertical and horizontal well, depending on the distribution of stresses and location of the well. Source: Valkó, 2009.

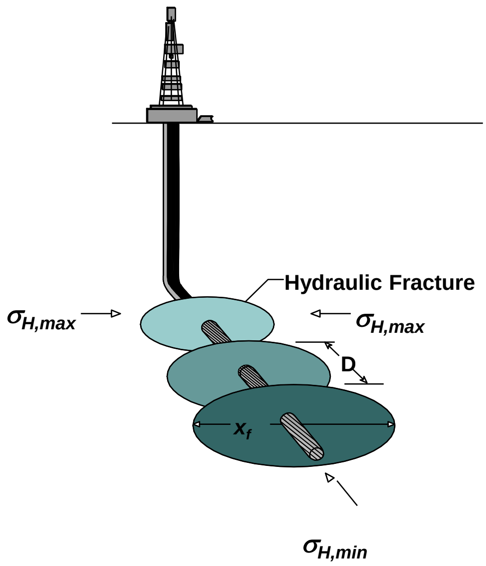

Figure 7b. Example formation of fractures perpendicular to the well axis. Source: Valkó, 2009.

The *slickwater* technology usually makes use of a greater quantity of water than the mixture, i.e. from 4 000 m^3 to 20,000 m^3 for fracturing in one well. This quantity will be lowered with the introduction of new technologies (King, 2012). Other chemical compositions used in the past were, e.g.: benzene, chromium. Those components are toxic and it was feared that they could potentially contaminate the water. At present they are hardly ever used in the fracturing operations on behalf of friendly chemistry (*green additives*), known from chemicals used in food industry (King, 2012; Shale Gas Primer, 2009).

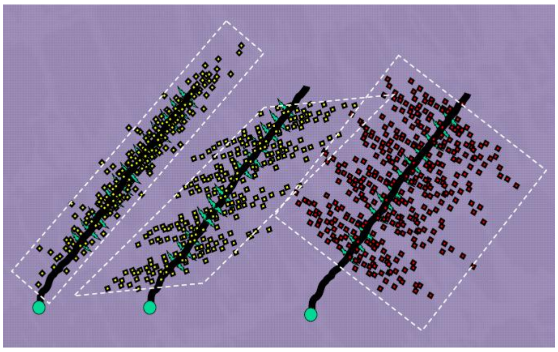

Figure 6. Grid of fractures around horizontal wells. Source: Mayerhofer et al., 2008.

Along with the fracturing fluid, the *proppant* is injected, i.e. backfilling, granulated sand or ceramic granules preventing against closing of the fracture wings. The main technological problem is transportation and maintaining *proppant* within the formed fracture, also above the area of maximum obtuseness.

Gas flow in shale rocks and fractures

Gas flows in shales through a system of nanopores connected with micropores. Gas desorption and diffusion in kerogen take place to the surface of contact with nanopores. The surface of desorption from nanopores is inversely proportional to the diameter of the nanopores d:

$$\left(S \sim \frac{4}{d}\right).$$

The scale of the phenomena accompanying shale gas exploitation can be classified in the following way:

- macro scale → gas flow to well;
- mezzo scale → flow in microspores, bigger pores and microfractures;
- micro scale → flow in nanopores with constant diffusion coefficient;
- nano scale → gas desorption from nanopore walls;
- molecular scale → gas diffusion in organic source matter (kerogen).

Each preceding type of flow or gas transport disturbs the thermodynamic equilibrium resulting in a successive flow. The flow in micropores and pores is described by the Navier-Stokes equation, and more precisely by the Darcy's Law being also a variation of the equation of motion. In nanopores we have gas flow with *a slide* on nanopore walls and molecular flow. These are completely different boundary conditions than those in Navier-Stokes problems, i.e. velocity of fluid particles on the walls is not equal to zero. The Knudsen number decides about the type of flow:

$$K_n = \frac{\lambda}{d} \quad (4)$$

and:

λ – is defined as a mean free way of gaseous molecules (determined from Boltzman's statistics) – reversely proportional to gas pressure;

d – diameter of nanopores

For Kn < 0.001 we have *continuum* fluid flow applicable to the Darcy's Law, d from 1 to 50 μm. For Kn: 0.001 < Kn < 1 the flow with *a slip*, d from 10 to 300 nm (1 nm = 10^{-9}m).

It can also be noted that methane flow in the coal beds is to a certain extent similar to the gas flow in shales, which also partly contain adsorbed gas.

The negative aspect of fracturing and other potential environmental hazards associated with shale gas exploitation

Most of media-generated information describing the usage of chemicals is based on data from the first operations performed in the year 2002 to 2007 (Shale Gas Primer, 2009). Meanwhile, the World keeps changing, also thanks to the activity of pro-ecologists fighting against nuclear energy (after the catastrophe in Chernobyl and Fukushima), coal-based energy (high CO_2 emission), coal degassing energy, etc. At present the environmental hazards are much lower than 5 to 10 years ago (King, 2012).

The basic documented cases encountered during drilling and gas production from unconventional sources in the USA are listed below in a table (MIT, 2011). From among 43 cases statistically analysed in 2006-2010, about 50% were contaminations of groundwater (gas migration to water), being a result of drilling operations. Such events may take place as a consequence of insufficiently protected columns cutting off groundwater fluxes and natural gas migration to the wells. Most of the observed cases in the report were related to coal-bed methane. Another environmental hazard was connected with leakages and contamination of oil products on the surface in the drilling site. No case of direct contamination of groundwater was observed in the process of fracturing (a case so called *Pavillon* in Wyoming is still being analysed by EPA (EPA, 2011). Such incidents reveal that in the process of drilling and gas exploitation some problems with the integrity of the protection system, especially in the case of shallow gas reservoirs, i.e. below 500 m bts, can be expected. The geological conditions in Poland are different; gas shales are deposited in deeper horizons, which may imply that such problems are just of theoretical character. The supervision of drilling operations by the State Mining Authority and General Department of Environmental Protection seems to be sufficient in this case.

Table 4. List of incidents related to exploitation of unconventional gas from classic reservoirs in 2006-2010 in the USA. Source: MIT, 2011.

Event	Number	%
Gas flow to groundwater	20	47%
Contamination of drilling site	14	33%
Problem with discharge of post-fracturing waste water	4	9%
Problems related to water intaking for fracturing	2	4%
Air pollution	1	2%
Gaseous eruptions in well	2	4%

The discussed cases should be juxtaposed with an immense number of gas wells drilled in the USA – tens of thousands each year. As a result we see that the influence of this type of environmental incidents is generally small. Obviously attention should be always paid to all environmental impacts as they may indirectly, to some minimal extent affect human health.

Hypothetical and real hazards associated with development of exploitation industry

Is exploitation of gas from these reservoirs also environmentally hazardous? Will economic conditions of gas exploitation, transport and sales be attractive to the investors? Will the economic, social and political atmosphere be favorable? What are the feasible directions and rate of development of this sector? These are the most important questions asked by investors and potential gas users in the energy sector. Basically, five main stages of construing unconventional gas sector can be distinguished (fig. 9):

1. Geological and geophysical exploration, test drillings. Geological risk. Resources.
2. Pilot drilling, profitability analysis of drilling, working out economic scenarios.
3. Making infrastructure, market analyses, long-term strategy of transportation and gas distribution.
4. Commercial drilling, starting up commercial production, creating new gas market.

Geological exploration

Geological recognition is a complex and long-lasting investigation process. One of its most important elements is the so-called *zero geological* *risk* (see fig. 10). As the geological risk is determined in the course of gas prospecting operations as certainty/uncertainty of gas/hydrocarbon presence, it is usually the shales for which *certainty* is noted in the sedimentary basin analysis. No such certainty exists for *tight* gas reservoirs, which constitute a considerable resource potential, but which more difficult to spot, recognize and manage. Additional information about state of recognition of Polish shale gas resources PIG (2012) & EIA (2011).

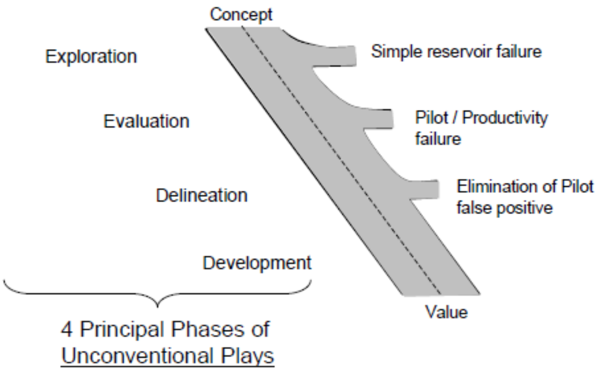

Figure 7. Main stages of development of gas engineering sector related to with gas production from unconventional sources. Source: Haskett, 2005.

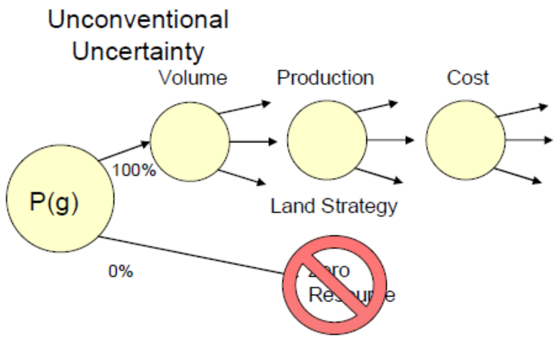

Figure 8. Risk and uncertainty related the formation exploitation and formation of gas market based on unconventional sources (zero geological risk).

Shale gas resources have not been clearly determined. They may differ in magnitude because of the available data, assumed methodology and simplifications. In March 2012 the Polish Geological Institute announced its results (PIG, 2012). They are much lower than the ones given so far. Even lower values were obtained by the USGS (2012). In 2009 the company Wood Mackenzie (Wood Mackenzie, 2009) estimated exploitable (beyond-balance) resources for 1400 billion m^3, whereas the Advanced Research Institute for 3000 billion m^3. According to the report from the US Energy Information Agency (EIA, 2011) performed by the Advanced Research Institute, the resources amount to 5300 billion m^3. Using the evaluation classic method, the company NSAI, with its seat in Houston (main auditor: C.H. (Scott) Rees III), predicted gas in place (within six concessions of company 3Legs Resources PLC – for Lane Energy Poland) for 5.1 to 5.5 billion m^3. NSAI assumed other, lower TOC values in its reports (accepted by exploitation companies). If the recovery factor remains at a level of 15 to 20%, the production in the concession area may be ca. 760-860 billion m^3 if the project is profitable (3Legs, 2011). Lane Energy does not give its figures for recoverable as the company has not started its exploitation yet.

Shale gas production potential and pilot exploration of unconventional sources

No pilot exploitation stage has been implemented in Poland yet. A few companies announced that they would start up production in two years' time, but this has to be treated with caution. Why? No serious company starts its activity without thorough economic analyses. Presently this is not possible because of the state of the art. The success in shale oil production is conditioned by technical possibilities in the context of applied technology of drilling, fracturing and petrophysical properties of rocks (65%), operating costs of gas production (15%) and performing the well (15%).

Can the pilot stage of gas development be omitted in Poland? Certainly not. This, however, will be a high economic risk activity, which can afford only companies which have their *energy safety* objective. The risk connected with such activities should be accepted by the company's main shareholders.

No pilot project of gas exploitation has been implemented in Poland yet and quite possible that they will certainly vary from the American ones. Only after making a sufficient number of pilot (exploitation) wells, e.g. 20 to 25 the economic feasibility of production in the entire basin can be determined. The most important is evaluation of average recoverable per one horizontal well (EUR); in the USA they are 30 to 140 mcm depending on geology and technology applied to the wells. The total estimated gas production from one well (EUR) is very important. The American experience reveals that a vertical well may yield maximum 60 to 70 mcm of gas over the total period of exploitation (King, 2012), and as much as 140 mcm from a horizontal one.

No possible assumptions are known as far as the length of the horizontal section, fracturing procedures in a new horizontal section or distance between wells go, which means that the *stimulated* zone of the well, i.e. volume of reservoir with artificially increased permeability cannot be determined. At present the volume of the stimulated zone increases gradually as new technologies are implemented. The American data prompt a conclusion that 35 to 45% of gas in place can be produced, which can soon be increased even to 55% with simultaneous reduction of the environmental impact (King, 2012). The relation between new technologies and the cost of gas production still remains

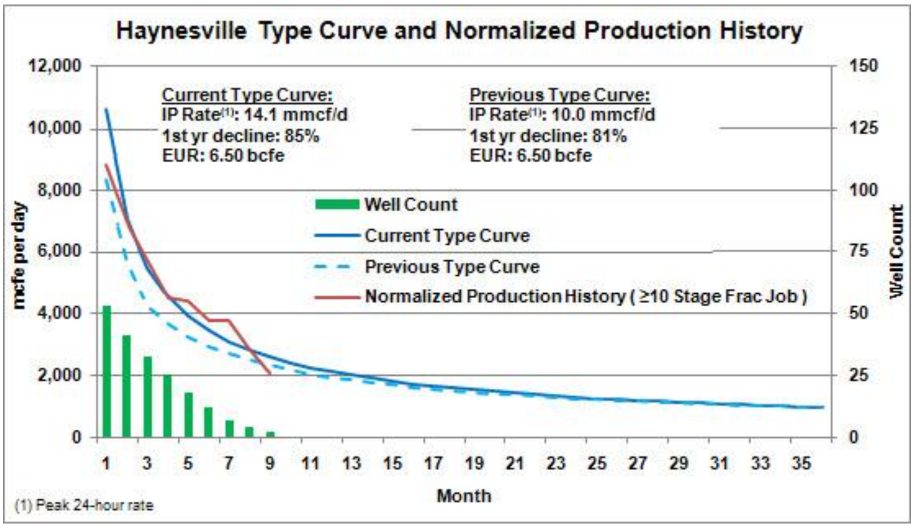

Figure 9. Influence of fracturing technology and exemplary decline curve of production at Haynesville gas field. Source: Chesapeake, 2009.

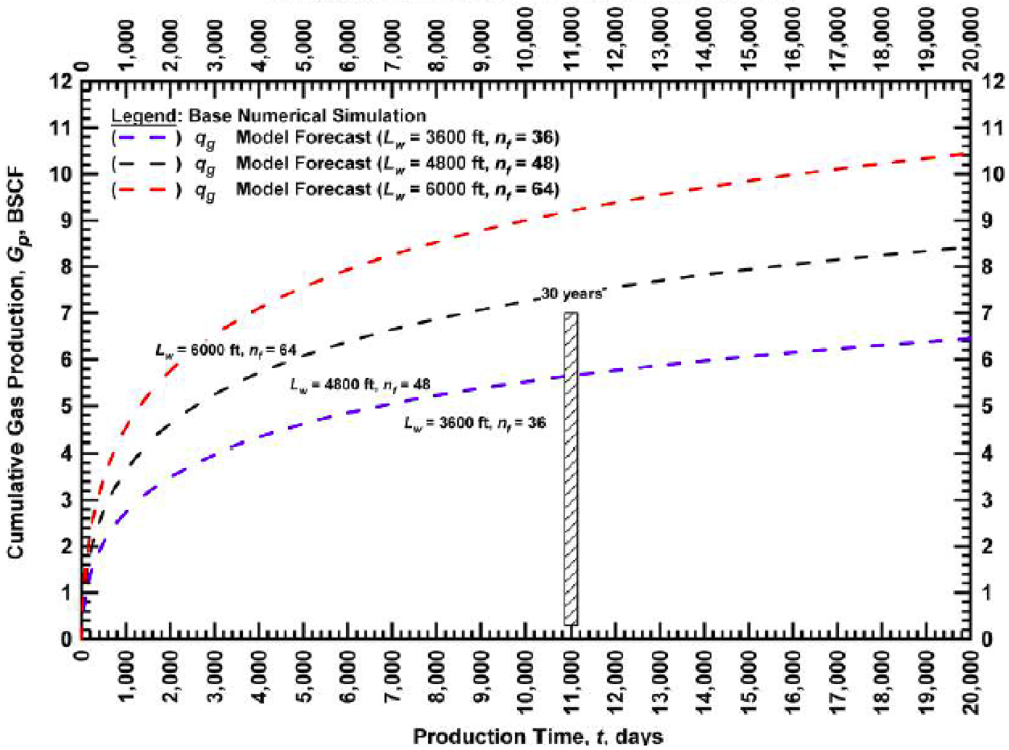

Figure 10. Influence of technology on total gas production from a single horizontal well. Source: Ilk et al., 2011.

unclear. The characteristic decline curves for one well at gas field Heynesville are shown in fig. 11, and the influence of fracturing technology on cumulative gas production in a well in fig. 12 (Ilk et. al., 2011).

The economic success will be conditioned by optimization of costs of drilling and increasing efficiency of fracturing. According to the author, these two elements need to be solved first. Some failures can be expected when developing the field: bad fracturing, drilling break-downs, unfavourable geological setting, etc. Depending on business, political, social and geological conditions a few different scenarios can be seen by the year 2025.

Four basic ones can be distinguished among them: optimistic, sustained (classic), sustained (pessimistic) and entirely pessimistic. Assumptions for those four scenarios are as follows:

1. Optimistic (rather unrealistic) scenario – simplified procedures, inflow of capital, accelerated investment for infrastructure, no objections, good simulation results, good exploitation parameters, low cost of drilling, fully accessible technologies, own research programs, reduced taxes (low production tax), the high profitability of investments.
2. Sustained (classic) scenario – delays related to environmental procedures, mediocre success in

Table 5. Example of development of shale gas exploitation for predefined number of drillings (from 150 to 290 wells yearly) (in mcm). The last slot gives the total annual gas production (in mcm). The analysis based on selected production profiles at the field Marcellus. Scenario No. 3a: sustained (pessimistic). Source: Chesapeake, 2009.

Number of wells drilled each year	**Assessed (exemplary) gas exploitation in years (mcm)**									
	Year 1	**Year 2**	**Year 3**	**Year 4**	**Year 5**	**Year 6**	**Year 7**	**Year 8**	**Year 9**	**Year 10**
150	2114	1010	800	678	619	582	570	542	514	489
200	0	2818	1347	1067	904	825	775	760	722	686
250	0	0	3523	1684	1333	1129	1031	969	950	903
260	0	0	0	3664	1751	1387	1175	1072	1008	988
270	0	0	0	0	3805	1819	1440	1220	1113	1047
270	0	0	0	0	0	3805	1819	1440	1220	1113
290	0	0	0	0	0	0	4087	1953	1547	1310
200	0	0	0	0	0	0	0	2818	1347	1067
200	0	0	0	0	0	0	0	0	2818	1347
200	0	0	0	0	0	0	0	0	0	2818
Total production (mcm)	2114	3829	5670	7092	8411	9546	10896	10774	11240	11767

Table 6. Example of development of annual shale gas production for predefined number of drillings (from 60 to 240 wells) (in mcm). The last slot gives the total annual gas production (in mcm). The analysis based on selected production profiles at the field Marcellus. Scenario No. 3a: sustained (pessimistic) – very slow drilling rate (Chesapeake, 2009).

Number of wells drilled each year	**Gas exploitation (mcm) – successive years from the beginning of**									
	Year 1	**Year 2**	**Year 3**	**Year 4**	**Year 5**	**Year 6**	**Year 7**	**Year 8**	**Year 9**	**Year 10**
60	845	404	320	271	247	233	228	217	206	195
80	0	1127	539	427	361	330	310	304	289	274
100	0	0	1409	674	533	452	412	388	380	361
120	0	0	0	1691	808	640	542	495	465	456
140	0	0	0	0	1973	943	747	632	577	543
160	0	0	0	0	0	2255	1078	853	723	660
180	0	0	0	0	0	0	2536	1213	960	813
200	0	0	0	0	0	0	0	2818	1347	1067
220	0	0	0	0	0	0	0	0	3100	1482
240	0	0	0	0	0	0	0	0	0	3382
Production in every year (mcm)	845	1531	2268	3062	3923	4852	5854	6920	8047	9233
Total gas production (mcm)	845	2377	4645	7707	11631	16483	22336	29256	37303	46536

Table 7. Probable/assessable periods for proper gas production. Source: Authors' own work.

Scenario	**Recognition of basins**	**Making pilot production**	**Decision about production start-up**	**Obtaining annual gas production of 10 billion Sm^3**	**Possible cost of gas production (USD/thousand Sm^3)**
Optimistic scenario	2012-2015	2013-2016?	2015/16?	2021/2023?	<210?
Sustained scenario no. 1	2012-2016	2014-2018?	2018?	2023/2026?	<260?
Sustained scenario no. 2 (pessimistic)	2012-2017	2014-2019?	2019?	2026/2032?	<300?
Pessimistic scenario	2012-2017	2015?	?	?	?

stimulation of wells, no support for home research programs, mediocre profitability (mean initial efficiency) of production, lowering of Russian gas prices.

3. Sustained (pessimistic) scenario – delayed environmental procedures, delays in making infrastructure, competitive prices of Russian gas.
4. The pessimistic scenario – withdrawal of the most important investors from Poland, no capital support for Polish companies, ecological obstacles blocking gas exploitation in Europe, maximum lowering of Russian gas prices.

Depending on the conditions, the development of particular scenarios will determine the start-up of commercial exploitation of shale reservoirs now or in the coming decade (tab. 7).

Conclusions

1. Geological setting which has not been fully recognized may hinder proceeding to the commercial stage of production without in-between stage of making pilot centre's where the efficiency of stimulation or cost of drilling and gas production can be optimized.

2. Restrictive environmental regulations, great number of protected areas and objects, negative opinions of local administration, bad organized logistics of supplies, hindered access to water resources may considerably lower the rate of industrial development.
3. New ecological technological solutions applied mainly in the USA show that technologies may be adjusted to local geological in Europe and Asia.
4. Challenges for technological development: high cost (cost and number of wells, the magnitude of the mine); infrastructure needed for gas transport and distribution, which should be made earlier when the commercial gas production is still uncertain; cost of the proper technologies.
5. The rate of industrial development will be also conditioned by the uncertain level of natural gas prices and possible instabilities in the market (type of contracts) – development of gas industry based on unconventional sources waits for strong support on the part of political, business and local authorities.
6. No additional taxes can be now levied on industry owing to considerable uncertainty in the conditions of production. In the initial period tax preferences should be introduced for companies in this sector, analogous to the USA in the 1990's.

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