Demonstration facility for underground coal gasification

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Introduction

Gasification is a group of multidirectional thermal and chemical transitions occurring at increased temperature between coal organic substance and gasifying agent, i.e. usually air, oxygen, steam or mixtures thereof. Depending on the process conditions, gasifying agent and coal properties, gas product is obtained with main components: hydrogen, carbon monoxide and dioxide, steam, methane. In case of air gasification, nitrogen is the main component of the gas. As thermodynamic balance is dominated by endothermic reactions, part of elemental carbon contained in the fuel (approx. 20%-30%) gets oxidised to carbon dioxide, while the heat obtained in exothermic reactions is used for other reactions [1].

Underground coal gasification from the chemical and thermodynamic perspective is analogous to the process carried out in surface reactors, especially with fixed bed. The essence of the process is obtaining coal chemical energy directly *in situ* by supplying gasifying agent to ignited coal seam and collection of produced gas on the surface.

Similarly to surface gasification, gas composition depends on type of gasifying agent, process parameter and raw material properties.

Underground coal gasification (UCG) process despite over 100 year history to this day has not implemented at the industrial scale, while research works – including experiments on different scales are carried out in different coal-rich countries with varying intensity since ca. 1920. In the last years, in connection with focus on the development of clean coal technologies and technological progress (i.a. directional drilling, remote monitoring of course of "controlled fire" underground) there is an increasing interest in this topic.

Polish research conducted mainly by the Central Mining Institute both in the past (1950's-60's) and currently focus on specific and rarely studied process variant – shaft method, i.e. using existing infrastructure of deep mines. Such earch direction despite additional difficulties resulting from conducting process in the rock mass affected by previous mining operations is due to the large amount of coal left underground after hundred years of mining (especially in the Upper Silesian Coal Basin). Its gasification can increase degree of seam utilization and thus contribute to rationalisation of the management of state natural resources. It is estimated that coal potentially useful for gasification after taking into account basic technical criteria (thickness, coal quality, seam continuity, tightness of geologic environment) can be present in operating mines in depth seams and seams down to 1000 m b.s.l. in amounts up to 845 mln t and 426 mln t, respectively. In liquidated mines, due to high fracturing of carboniferous rock mass no coal reserves were distinguished.

The aim of the paper is to present selected results of research connected with development of underground coal gasification facility of designed power 12 MW in chemical energy of process gas. The paper was prepared for the purposes of supplying industrial recipient in order to replace previously used power resources (coal and E-type natural gas). The following assumptions are presented: georeactor location, main geological data and spatial configuration of technological system along with calculation results of enterprise cost-effectiveness.

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Underground gasification methods

Fundamental difference between surface gasification (SCG) and underground gasification (UCG) lies in different conditions, under which the process is carried out. In case of SCG, the facility can be constructed at any distance from the coal source. The supplied coal can be transported and prepared in a manner depending on the type of reactor. In case of UCG, the facility is "bound" by location to a specific coal deposit. The configuration of underground part depends on seam conditions of coal bed and equipment level of underground infrastructure; there can be distinguished two main process methods – shaft method and well method. Shaft method involves utilization of existing shafts and excavations of the mine under liquidation for laying process pipelines and drilling generator holes. Bore method involves accessing coal seam in the region, which has not been exploited yet by means of drilling from the surface.

In both cases, a fundamental component of the underground part of facility is georeactor. This name is used for the space, where gasification reactions occur. Georeactor shape and configuration depends on the system of preliminary drilled wells making the seam available. Currently, two georeactor configurations are most often used: one-well, where the process occurs along the horizontal well conducted on seam thill in direction from gas collection towards supply point (the name CRIP – controlled retractable injection procedure is used in the literature) or two-well method, where process occurs between two horizontal bores drilled on the thill joined together at the end in the place where reaction is initiated (coal ignition) and towards their beginning. Both designs are used both in shaft and well method, preferably executed by means of directional drilling that provides precision of executing long bores in the seam despite disturbances in its course, and in case of two-well reactor there is an additional option to join the wells.

Demonstration facility, according to its name is to be used to verify technical and process solutions prior to their application at industrial scale. The construction of the facility at that scale is especially justified in case of complex technologies that have high potential of innovative solutions. UCG shaft method satisfies these conditions.

Assumptions for the demonstration facility [2]

Based on the literature review and experiment conducted successfully on pilot scale in 2014 at KHW S.A. KWK Wieczorek, size of the facility was preliminary determined to be 20 MW of useful energy (electricity and heat). The size was verified at the stage of searching for location of demonstration gasification plant. The verification of facility performance resulted from the following reasons: limitations and objection regarding location of surface part of the gasification plant, deposit conditions allowing long-term and safe operation of the facility, rationalisation of the gas consumption in the facility for power producing combustion located near the gasification plant. Presented conditions resulted from assumption that in case of positive result of demonstration trial the following possibility can be taken into account: plant expansion in the underground part and its transformation into commercial facility.

After analysis of numerous options, as an exemplary location of facility for the purposes of design development and preliminary feasibility study an option was selected that can be described in the following manner: gasification in seam 334/2 in one of the mines of KHW S.A., gas outlet at the area of ventilation shaft of the mine – to the surface part of the facility, gas supply to combustion system at the receiver operating at distance of approx. 610 m from the shaft – to use gas for supply of duel fuel boiler of total capacity of 20.5 MW or as an alternative – gas boiler room supplied with GZ 50 gas and gas from gasification serving the residential estate to be constructed near by. Figure 1 basic design components are indicated.

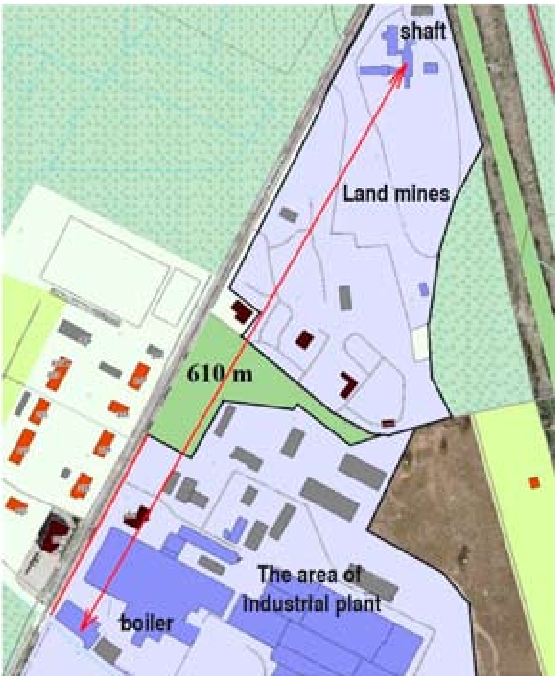

Fig.1. Location of the main elements of the demonstration installation

The analysis of the predicted average energy demand by the company, where the gas can be used, have shown that after taking into account power distribution curve and providing minimum boiler grate load with coal, design value of chemical enthalpy flow of purified gas supplied from gasification to combustion is an equivalent of approx. 12 MW. Similar value of gas enthalpy flow from gasification (12 MW) was assumed for gas boiler of total capacity of approx. 20 MW.

Underground coal gasification demonstration facility consists of underground and surface part. In the surface part the following main systems can be distinguished:

1. Gas media supply system:
   - system of compressed air used as gasifying agent,
   - oxygen tank and evaporator – medium used for igniting the georeactor and adjust gas composition,
   - nitrogen tank and evaporator – medium used as protective gas and at initial stage of extinguishing the georeactor.
2. Gas collection, cooling and purification system to obtain degree required by boiler burners:
   – venturi scrubber with water circulation,
   – oil scrubber,
   – condenser system,
   – gas drying system using glycol,
   – sulphur compound adsorbers with regeneration possibility.

   The system includes also turboexpander and emergency and excess gas flare, which pilot burners are supplied with GZ 50 gas from the network.
3. Liquid condensed product (water, tar) collection system, phase separation system, storage and distribution to wastewater receiver (settling tank).
4. Gas pipeline to the collector.
5. Electricity and water supply systems from the mains.

Diagram of surface part of the facility is presented in Figure 2.

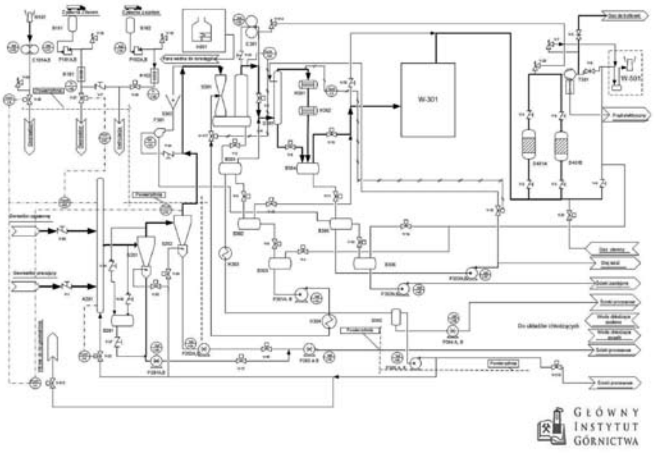

Fig. 2. Scheme of the supply installation and gas collection system

In the underground part main systems are:

- set of main and secondary pipelines for supplying gasifying agent and product collection in the shaft from level 416
- four georeactors executed by means of directional drilling from the level 416 to seam 334/2 outside the mining protection area of the shaft; each georeactor is available through two parallel bores of 200 mm diameter at angle of approx. 40° to the level downwards and approx. 500 m length; distance between bores – 20 m; after reaching the seam, the bores are on thill, after 300 m they change direction horizontally in order to join each other; bores in the section from shaft to the seam are tubed
- gas pretreatment system (collector with water injection, cyclones) is located in excavations at 416 level; the system is equipped with pumps supplying water-tar condensate to the surface to the settling tank.

Diagram of georeactors system in the seam 334/2 is presented in Figure 3.

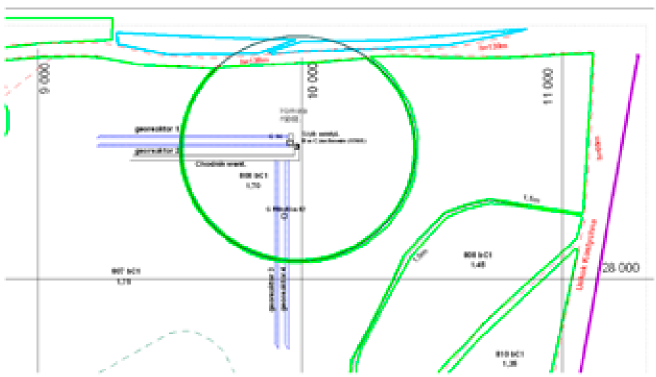

Fig. 3. The georeactors' system in the coal bed

Main assumed process parameters of the installation operation were determined based on data obtained experimentally at pilot scale in KHW S.A.KWK Wieczorek in 2014, supplemented with model calculations and results of large laboratory scale and data reported from tests conducted in various countries of similar environment. In Table 1 main process data are presented; dual fuel boiler efficiency presented in position 8 is a result of analysis of efficiency of operating boiler unit, which average annual efficiency is 78% and adjustments for combustion of UCG gas.

Table 1

Main data of the UCG shaft method pilot installation – air gasification

No.	Property, unit	Value
1	UCG gas enthalpy flow, MW	12
2	Maximum design gas temperature at georeactors' outlet, °C	550
3	UCG gas temperature at shaft outlet to surface installation, °C	100-280
4	Design pressure in georeactor, MPa	7.0
5	Maximum flow of gasification air, Nm3/h	6,950
6	Maximum raw gas flow, Nm^3/h	12,400
7	Cold gasification efficiency, %	60-66
8	Dual fuel boiler efficiency, %	73
9	Seam thickness, m	1.7
10	Depth of deposition, m b.s.l.	700
11	Inclination of seam	2° in SW
12	Coal parameters in seam: coal type ash content, % moisture content, % volatile matter content, % total sulphur content, % calorific value, MJ/kg	 32.1 8.84 8 38 0.61 28

For the assumed gas enthalpy flow of 12 MW and assumed process efficiency, amount of gasified coal of calorific value of 28 MJ/kg will 1.9-2.7 t/h.

Quantity of coal for one year operation of underground part of installation (7000 hours/year) and seam utilization degree of 0.55 is determined to be 24-35k tonnes. Estimated balance coal resources in the area of the shaft, limited by main faults are equal to 10,515 mln tonnes, while exploitable resources are 6,309 mln tonnes. Maximum quantity of coal planned for gasification in single georeactor is approx. 14,000 t. It results from this that possible georeactor operation time at maximum load (2.7 tonnes/hour) will be approx. 7.2 months. Main product of the installation will be a gas of composition presented in Table 2.

Table 2

Composition of raw UCG gas

No.	Component, molar fraction, % vol.	Value
1	- hydrogen - carbon monoxide - steam - nitrogen - carbon dioxide - methane - hydrogen sulphide	6.58 2.52 22.11 42.56 17.83 8.11 0.09
2	Tar content in gas, g/Nm^3	5.0
3	Raw gas calorific value, MJ/Nm^3	4.6
4	Treated gas calorific value, MJ/Nm^3	5.33

Financial analysis [3]

For the presented concept of demonstration installation a financial analysis in two variants was conducted:

Variant 1 (V1): heat generation installation for technological needs of the company of total heat capacity 20.5 MW_{Th}, including 12 MW_{Th} in UCG gas: co-combustion of UCG gas with coal in dual fuel boiler.

Variant 2 (V2): heat generation installation for commercial needs (sales to individual customers) of total heat capacity 20.5 MW_{Th}, including 12 MW_{Th} in UCG gas: co-combustion of UCG gas with natural gas in gas boiler. This is only a modification of variant V1 in the surface part: instead of modernisation of coal boiler for utilization of UCG gas, a construction of boiler room supplied with process gas and natural gas.

Financial analysis was conducted for fixed prices, which allowed avoiding errors resulting from long-term inflation forecasts.

For both variants (V1 and V2) the same life cycle was assumed, of 20 years, which corresponds with average operation time of power generation installation of the analysed scale. Investment period (installation construction) was assumed to be 20 years. Due to the impossibility of actual estimation of value of process infrastructure of UCG facility and heat generation facility within 20 years, residual value in the analysis was omitted. Omission of residual value in analyses is also justified by the fact that potential revenues from the sale of surface infrastructure will be used to secure exploited underground infrastructure. Analyses by means of UNIDO were conducted for discount rate of 3.37% determined on the basis of analysis of WIBOR 3M and bank margin related to granted credits in the period from January 2010 to April 2015.

For the variant V1, financial analysis was conducted by differential method for which reference ("zero" variant – V0) was the investment assuming modernisation of the existing boiler – recovering its efficiency and heat generation only by coal combustion. Benefits for the variant V1 are avoided investments for such a modernization of the existing boiler and savings in the expenses for col partially replaced by UCG gas.

In case of variant V2 there is no "zero" variant – this is a financial analysis of the complete investment "from scratch", where on the revenue side revenues from sale of heat to individual customers. Unit base price of the generated heat was assumed after the Information of the Chairman of the Energy Regulatory Authority (URE) according to which average heat sale price in 2014 stood at 75.66 PLN/GJ in the generating units firing gaseous fuels [4]. The analysis was conducted for the assumed prices of the 1st quarter of 2015. In the subsequent years, base values of adopted or estimated for 2015 operation costs (including coal and natural gas costs) are adjusted with macroeconomic and forecast indicators [6, 7]. Used in calculations, investment outlays and operation costs are estimates calculated based on the design documentation of the UCG demo installation [2]. The calculations account for current stock prices for purchase of CO_2 emission rights (as in April 2015), i.e. approx. 7.5 EURO/t CO_2 [5]. Costs of obtaining gasified goal are taken into account in the form of operation fee, which due to the lack of legislation in this scope for underground coal gasification was assumed to be equal to fee paid for coal mining. Results of calculations of investment outlays and operation costs are presented in Table 3 and 4.

In the analysed technological variant V1 assuming co-combustion of process gas with goal for heat generation, the obtained NPV indicator value indicates lack of economic efficiency of the investment. IRR and DPP indicators does not exist, as in the entire analysis period there are negative cash flows – savings due to the decreased coal consumption are much lower than operation costs of UCG gas production facility. This is a result of necessity to incur in this variant significant including for construction of underground and surface gas production infrastructure and subsequent expensive operation of the facility. This translates into high gas production cost, which in this case is not competitive in relation to coal used for heat production. Based on the obtained results, one can generally conclude that process gas obtained in the UCG cannot compete with hard coal in terms of price, if it is used for production of heat; however, it is competitively priced in relation to natural gas bought from network. However, one needs to take into account limited possibilities of application of process gas in comparison to natural gas due to much lower calorific value or content of hazardous substances (e.g. carbon monoxide).

Table 3

Summary of investment and operating costs for the underground part of the analyzed UCG demonstration facility

Position	Unit	Unit cost / basis for calculation [PLN]	Amount per structure	Life cycle - depreciation base [years]	Amount per operation year	Total costs [PLN or PLN/year]	
UNDERGROUND PART							
Investment							
Pipelines in the shaft 150 mm (2 pcs). - gasification agent	m	500	750	10	-	375,000	PLN
Pipelines in the shaft 150 mm (2 pcs). - process gas	m	600	750	4	-	450,000	PLN
Underground equipment (pumps, gas treatment)	set	1,200,000	1	5	-	1,200,000	PLN
Data collection and transmission system	pcs.	500,000	1	5	-	500,000	PLN
Safety systems	pcs.	800,000	1	4	-	800,000	PLN
TOTAL INVESTMENT OUTLAYS - underground part	-	-	-	-	-	3,325,000	PLN
Operation costs							
Pipeline 150 mm shaft-georeactors 1 and 2: gasification agent	m	500	80	5	16	8,000	PLN/year
Pipeline 150 mm shaft-georeactors 1 and 2: process gas	m	600	80	2	40	24,000	PLN/year
Pipeline 150 mm shaft-georeactors 3 and 4: gasification agent	m	500	70	5	14	7,000	PLN/year
Pipeline 150 mm shaft-georeactors 3 and 4: process gas	m	600	70	2	35	21,000	PLN/year
Pipeline 150 mm shaft-georeactors n and n+1: gasification agent	m	500	500	5	100	50,000	PLN/year
Pipeline 150 mm shaft-georeactors n and n+1: process gas	m	600	500	2	250	150,000	PLN/year
Directional drilling 200 mm for 1 georeactor	m	2,000	1,000	0.46	2,174	4,347,800	PLN/year
Access gallery	m	20,000	0	1	0	0	PLN/year
Preparation of technical conditions for UCG process	set	1,000,000	1	1	1	1,000,000	PLN/year
Salaries with related surcharges	jobs	5,000	24	-	-	1,440,000	PLN/year
Electricity	MWh	280	1,200	-	1,200	336,000	PLN/year
Materials, technical gases, overhauls i maintenance	% outlays for fixed assets	3,325,000	1	-	5.0%	166,250	PLN/year
Operation charge	PLN/Mg	2.31	1	-	23,652	54,636	PLN/year
Taxes and insurance costs	% outlays for fixed assets	3,325,000	1	-	3.0%	99,750	PLN/year
Amortisation and depreciation	% outlays for fixed assets	3,325,000	1	-	-	690,000	PLN/year

Source: [2], own calculations

Results of financial analysis are presented in Table 5.

Table 5

Economic efficiency indicators for the demonstration facility

Economic efficiency indicator, unit	Variant 1	Variant 2
NPV - net present value, PLN	-232,416,412	36,323,509
IRR - Internal rate of revenue, %	N/A	12.8%
DPP - discounted payback period, years	N/A	7.0

Summary

One of the ways of compromise between use of national riches, i.e. coal resources, for power generation and sustainable development with rational use of natural resources in manner guaranteeing minimization of negative impact on the environment and human health is implementation of clean coal technologies that include underground coal gasification.

The specifics of Polish hard coal resources involves its significant exploitation level, especially in the Upper Silesian Coal Basin area. Therefore, shaft UCG method is of special interest as it allows management of selected plots in seams left in liquidated mines and depth seams. In this manner, according to the principle of sustainable development, there is an increase of coal utilization degree, particularly for satisfying local power needs.

Previous Polish studies of this technology, especially pilot trial conducted in 2014 in KHW S.A. KWK Wieczorek, provide good base for further research with next stage involving construction of demonstration facility. The innovativeness of the shaft method, little technical and economic information regarding this method in global literature, fully justifies construction of the facility on this scale. Its operation shall provide data necessary to decide whether to commercialize this technology.

The process design along with preliminary feasibility study may be a basis for decision on the construction of demonstration facility. The design was developed under the Task 3 "Development of coal

Table 4

Summary of investment and operating costs for the surface part of the analyzed UCG demonstration plant

Position	Unit	Unit cost / basis for calculation PLN/unit	Amount per structure	Life cycle - depreciation base years	Investment outlays / operation costs PLN or PLN/year	
SURFACE PART						
Investment						
Surface pipelines with equipment and devices for preparation of gasifying agent and treatment of process gas	set	11,000,000	1	10	11,000,000	PLN
Pipeline of process gas 600 mm at distance of shaft-boiler room	m	500	700	20	350,000	PLN
W0 – boiler modernisation – existing variant (coal firing)	pcs.	1,600,000	1	20	1,600,000	PLN
V1 – boiler modernisation – analysed variant (co-combustion of process gas and coal)	pcs.	2,800,000	1	20	2,800,000	PLN
V2 – Construction of 25 MWth boiler room for the purposes of heat generation	set	25,700,000	1	20	25,700,000	PLN
TOTAL INVESTMENT OUTLAYS for V1 – surface part	-	-	-	-	**14,150,000**	**PLN**
TOTAL INVESTMENT OUTLAYS for V2 – surface part	-	-	-	-	**37,050,000**	**PLN**
Operation costs						
Electricity – consumption by surface systems	MWh	280	2,400	-	672,000	PLN/year
Chemicals – surface systems	Mg	-	-	-	400,000	PLN/year
Salaries with related surcharges - V1 and V2	jobs	5,000	10	-	600,000	PLN/year
Coal - V1	Mg/year	197	24,300	-	4,787,100	PLN/year
Network natural gas - V2	m^3/year	1.11	19,080,000	-	21,089,106	PLN/year
Materials, overhauls and maintenance - V1	% outlays for fixed assets	14,150,000	5.0%	-	707,500	PLN/year
Materials, overhauls and maintenance - V2	% outlays for fixed assets	37,050,000	5.0%	-	1,852,500	PLN/year
Environmental charges – V1	Mg	-	-	-	715,906	PLN/year
Environmental charges – V2	Mg	-	-	-	501,134	PLN/year
Purchase costs of CO_2 emission rights - V1	Mg	30	55,188	-	2,832,327	PLN/year
Purchase costs of CO_2 emission rights - V2	Mg	30	38,632	-	1,982,629	PLN/year
Taxes and insurance costs - V1	% outlays for fixed assets	14,150,000	3.0%	-	424,500	PLN/year
Taxes and insurance costs - V2	% outlays for fixed assets	37,050,000	3.0%	-	1,111,500	PLN/year
Amortisation and depreciation – V1	PLN/year	-	-	-	1,257,500	PLN/year
Amortisation and depreciation – V2	PLN/year	-	-	-	2,402,500	PLN/year

Source: [2], own calculations

gasification technology for highly efficient production of fuels and electricity under the strategic research and development programme "Advanced technologies for energy generation". The project, based in the reality of one of KHW S.A. mines is a summary of current research stage of shaft method conducted not only under this project, but also in the FBWiS projects of acronyms HUGE and HUGE 2, as well as under project conducted under Polish-Ukrainian cooperation in the years 2009-2011. Preliminary feasibility study indicates economic possibility of the investment after taking into account specific conditions, especially regarding methods of utilization of gas for power production.

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Nagrody Fundacji na rzecz Nauki Polskiej 2015 wręczone
Fundacja na rzecz Nauki Polskiej po raz 24. wręczyła Nagrody Fundacji, które cieszą się opinią najważniejszego wyróżnienia naukowego w Polsce. Podczas uroczystości, która odbyła się 2 grudnia br. na Zamku Królewskim w Warszawie, wyróżnienie odebrali wybitni polscy uczeni – prof. Stanisław Penczek, prof. Kazimierz Rzążewski i prof. Jerzy Jedlicki. Nagrody Fundacji są przyznawane za szczególne osiągnięcia i odkrycia naukowe, które przesuwają granice poznania i otwierają nowe perspektywy poznawcze, wnoszą wybitny wkład w postęp cywilizacyjny i kulturowy naszego kraju oraz zapewniają Polsce znaczące miejsce w podejmowaniu najbardziej ambitnych wyzwań współczesnego świata. Wysokość nagrody wynosi 200 tys. zł. Nagrody są przyznawane w czterech obszarach: nauk o życiu i o Ziemi, nauk chemicznych i o materiałach, nauk matematyczno-fizycznych i inżynierskich oraz nauk humanistycznych i społecznych. Prof. Stanisław Penczek z Centrum Badań Molekularnych i Makromolekularnych PAN w Łodzi otrzymał Nagrodę FNP 2015 w obszarze nauk chemicznych i o materiałach za opracowanie teorii polimeryzacji z otwarciem pierścienia i jej wykorzystanie do syntezy polimerów biodegradowalnych.

Prof. Kazimierz Rzążewski z Centrum Fizyki Teoretycznej PAN w Warszawie otrzymał Nagrodę FNP 2015 w obszarze nauk matematyczno-fizycznych i inżynierskich za odkrycie zjawiska magnetostrykcji w ultra-zimnych gazach z oddziaływaniem dipolowym.

Prof. Jerzy Jedlicki z Instytutu Historii im. Tadeusza Manteuffla PAN w Warszawie otrzymał Nagrodę FNP 2015 w obszarze nauk humanistycznych i społecznych za fundamentalne studia nad fenomenem inteligencji jako warstwy społecznej i jej rolą w procesach modernizacji w Europie Środkowo-Wschodniej.

W obszarze nauk o życiu i o Ziemi w 2015 r. Nagrody nie przyznano. Kandydatów do Nagrody FNP, zgodnie z jej regulaminem, zgłaszać mogą wybitni przedstawiciele nauki zaproszeni imiennie przez Zarząd i Radę Fundacji. Rolę Kapituły konkursu pełni Rada Fundacji, która dokonuje wyboru laureatów na podstawie opinii niezależnych recenzentów i ekspertów oceniających dorobek kandydatów.

Wideo i pliki graficzne: http://centrumprasowe.pap.pl/cp/pl/news/info/44005,,nagrody-fundacji-na-rzecz-nauki-polskiej-2015-wreczone
Źródło informacji: Fundacja na rzecz Nauki Polskiej *(abc)*

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