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# ENVIRONMENT FRIENDLY COAL PROCESSING TECHNOLOGIES FOR SUSTAINABLE DEVELOPMENT OF POLISH ENERGY SECTOR

## PRZYJAZNE ŚRODOWISKU TECHNOLOGIE PRZETWÓRSTWA WĘGLA DLA ZRÓWNOWAŻONEGO ROZWOJU POLSKIEGO SEKTORA ENERGETYCZNEGO

**Abstract:** According to the projections, world net electricity production is predicted to increase from 18.0 trillion kWh in 2006 to 31.8 trillion kWh in 2030. Coal contribution to world electricity supply remains the highest and is said to even slightly increase to 43% in 2030. Being the most abundant and competitive, coal recoverable reserves could satisfy the world's energy needs in the perspective of about 120 years at the current consumption levels. There is, however, a need for further improvement of coal-fired power generation in terms of its economics and environmental impact. The so-called Clean Coal Technologies (CCT) enabling energy efficient and environmentally friendly use of coal include: coal upgrading, improvements in efficiency of existing power plants, advanced power generation technologies, near zero-emission technologies and technologies for $CO_2$ transport and storage. In the paper the future role of coal in energy systems with a special focus on Polish energy policy, and the main trends in coal processing in the aspect of Clean Coal Technologies are presented.

**Keywords:** coal, processing, energy

## Introduction

A continuous increase in the demand as well as in the share of coal in the energy consumption and electricity production is declared in the reports and forecasts for energy sector. In 2006 the respective values equaled 11,800 $Mt_{oe}$, 27% and 42% [1]. The energy demand is expected to reach 16,950 $Mt_{oe}$ in 2030 and the share of coal in the energy consumption and power generation are said to be on the similar significant levels of 28% and 42% for it is regarded as a safe and reliable fuel, available from large reserves and worldwide market free of geopolitical constraints, when compared with other fossil fuels as crude oil or natural gas.

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The estimates of coal R/P ratio (*proved reserves to production*) in 2009 support the forecast for its future major role in energy mix as its reserves are said to be sufficient for 122 years, while those of crude oil and natural gas for 42 and 60 years, respectively.

The prices of coal are generally lower and more predictable than prices of crude oil fluctuating in the last decade from about 14 to above 70 USD/bbl* (with a peak in 2008 of 100 USD/bbl) and prices of natural gas dependent on the latter ones [2]. Coal price levels in the relevant period in Northwest Europe have risen from about 30 to 80 USD/ton (with a peak in 2008 of about 150 USD/ton). Storage and transport of coal is also economically competitive, eg it does not require high pressure pipelines.

Nevertheless, coal is considered the most carbon-intensive fuel. Global dependence on all fossil fuels since the mid-19th century led to the release of over 1100 $GtCO_2$ into the atmosphere [3]. World $CO_2$ emissions from fuel combustion account for about 70% of total *greenhouse gas* (GHG) emissions and 80% of total $CO_2$ emission [4]. The emission of $CO_2$ from energy sector is expected to grow from 29.0 billion metric tons in 2006 to 40.4 billion metric tons in 2030. Coal share in world $CO_2$ emissions is also expected to grow from 42% in 2006 to 45% in 2030 [1].

In the light of the above, the technologies aiming at more sustainable coal processing, the so-called *Clean Coal Technologies* (CCT) are of special importance in regard to economies with energy sectors heavily dependent on coal. The paper presents the up-to-date trends in coal utilization technologies for energy needs in the aspect of CCT and characteristics of Polish energy system, with a special emphasis put on coal gasification with $CO_2$ capture.

## Clean Coal Technologies

Coal processing technologies are regarded as one of the most $CO_2$ intensive with present-day 42% share in fossil fuels-based $CO_2$ emission [5]. But with an increasing deployment of energy efficient and low carbon technologies coal could be considered addressing its environmental challenges.

The term Clean Coal Technologies refers to technologies developed and implemented in order to mitigate the negative environmental impact of coal utilization. During about 40 years of CCT development the focus in CCT moved from $SO_2$, $NO_x$, Hg and dust emissions reduction to GHG emission reduction, with a special emphasis put on *carbon capture and storage* (CCS) technologies. At present there are five groups of technologies with a high potential for $CO_2$ reduction from coal processing specified by the International Energy Agency (IEA). These include coal upgrading, improvements in efficiency of existing power plants, advanced power generation technologies (eg *Integrated Gasification Combined Cycle*, IGCC), near zero-emission technologies and technologies for $CO_2$ transport and storage. It is estimated that wider deployment of coal upgrading technologies, well-established in developed countries, such as coal washing, drying and briquetting, could contribute to 5% $CO_2$ emission reduction, while increasing thermal efficiency of existing coal-fired power plants to 40% by equipment upgrading and monitoring would reduce it by 22% [6].

* bbl - barrel

Advanced power generation technologies include *supercritical* (SC) and *ultrasupercritical* (USC) giving outlet steam temperature of 540÷566°C at 250 bar and over 590°C under pressure over 250 bar, respectively. Increased thermal efficiency of up to 45% at present and 50% expected in the future (with IGCC or *Pressurised Fluidized Bed Combustion*, PFBC) results in lower levels of $CO_2$, which would have to be captured per kWh produced.

The IGCC technology has been under development for about thirty years now. The level of operating expertise required for its economic competitiveness still has not been reached, though there are examples of commercial-scale facilities operating worldwide.

In the gasification process known since the 19th century coal is converted into synthesis gas.

The first step of gasification process is pyrolysis, taking place at temperatures above 400°C, resulting in carbon-rich char and hydrogen-rich volatiles production in the absence of oxygen. In the second step, at temperatures over 700°C, the char is gasified. In the IGCC process the *water gas shift* (WGS) step is introduced to convert CO into $CO_2$ and thus increase the $CO_2$ content in the final gas. The following reactions between coal and gasifying medium, like oxygen and/or steam can be distinguished (the heats of reactions are calculated for 850°C using HSC Chemistry ver.3.0 [7]):

$$C + O_{2(g)} \rightarrow CO_{2(g)} \quad \Delta H = -394.9 \text{ kJ/mol} \tag{1}$$

$$C + 0.5O_{2(g)} \rightarrow CO_{(g)} \quad \Delta H = -113.0 \text{ kJ/mol} \tag{2}$$

$$CO + 0.5O_{2(g)} \rightarrow CO_{2(g)} \quad \Delta H = -281.9 \text{ kJ/mol} \tag{3}$$

$$C + H_2O_{(g)} \rightarrow CO_{(g)} + H_{2(g)} \quad \Delta H = +135.7 \text{ kJ/mol} \tag{4}$$

$$CO_{(g)} + H_2O_{(g)} \rightarrow CO_{2(g)} + H_{2(g)} \quad \Delta H = -33.2 \text{ kJ/mol} \tag{5}$$

$$2CO_{(g)} \rightarrow CO_{2(g)} + C \quad \Delta H = -168.9 \text{ kJ/mol} \tag{6}$$

$$CH_{4(g)} + H_2O_{(g)} \rightarrow CO_{(g)} + 3H_{2(g)} \quad \Delta H = +226.7 \text{ kJ/mol} \tag{7}$$

$$C + 2H_{2(g)} \rightarrow CH_{4(g)} \quad \Delta H = -91.020 \text{ kJ/mol} \tag{8}$$

$$CH_{4(g)} + CO_{2(g)} \rightarrow 2CO_{(g)} + 2H_{2(g)} \quad \Delta H = +259.942 \text{ kJ/mol} \tag{9}$$

In general, gasification technology and IGCC in particularly, offers higher potential efficiencies, wider variety of feedstock and products (eg electricity, synthetic natural gas SNG, $H_2$, chemicals) when compared with SC or USC.

The CCT focus is moving in developed countries from conventional pollutants emission control to decarbonization of coal processing by increasing efficiency and $CO_2$ capture and storage.

CCS technologies are of special importance in the light of Kyoto Protocol targets, increasing energy demand and role of fossil fuels in energy supply.

The technologies for $CO_2$ separation have been used in industry for a century now but with and aim of producing pure $CO_2$ streams rather than of its emission mitigation. $CO_2$ capture is performed among the others in purification of natural gas and in chemical plants for ammonia, alcohols and liquid fuel production. One of the processes of $CO_2$ separation from methane in natural gas treatment is chemical absorption. Amine scrubbing could be also used in post-combustion $CO_2$ capture processes, applicable for conventional coal-fired power generation and gas-fired power generation using combustion turbines. In this case, however, the $CO_2$ concentration in the gaseous mixture is lower, about 14%, and the relevant energy cost for new power plants is 20÷25% of plant output, resulting from the energy requirements of the process (for $CO_2$ desorption from the amine solution, dehydration and compression) and reduced plant efficiency. The chemical absorption and other components of the post-combustion capture systems, although operated commercially, have not been used and optimized for large scale of coal-fired plants yet. Still, they are attractive in terms of modernization of the existing plants.

In oxyfuel combustion process, operated in a number of system worldwide, coal is burned in oxygen. The flue gas is mostly $CO_2$ and thus the cost of amine scrubbing is about half the cost of $CO_2$ capture from conventional plants. The cost of air separation unit operation for oxygen production is however considerable. It is applicable to *pulverized coal* (PC) oxygen-fired combustion in an enriched oxygen environment using pure oxygen diluted with recycled $CO_2$ or $H_2O$. In the oxy-combustion process with flue gases recirculation: $O_2/CO_2$, fuel is combusted in the mixture of oxygen and $CO_2$, which is next recycled with flue gases for combustion temperature control. In a result the flue gases contain mainly $CO_2$ and steam, which can be condensed. The resulting gas stream contains high concentration of sequestration ready $CO_2$.

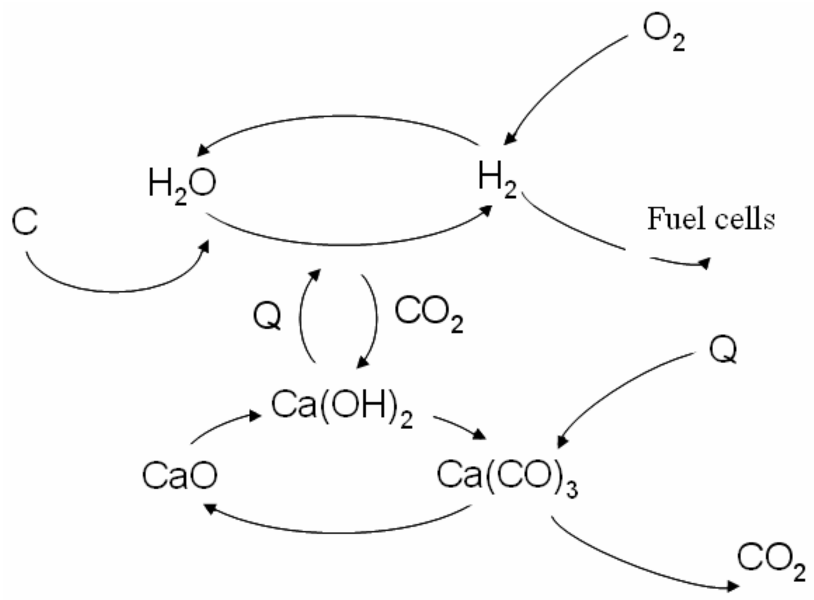


Fig. 1. The idea of the HyPr-RING process. Based on [10]

The pre-combustion $CO_2$ capture is applicable to gasification plants. It is suitable to be used in the IGCC plants where coal is gasified with steam to gas composed of hydrogen and carbon monoxide, which is further converted in WGS reactors to hydrogen and carbon dioxide mixture. After separation hydrogen is used as a fuel and carbon dioxide is ready for sequestration. Still no commercial scale system of this type is operated yet.

A novel method of the pre-combustion $CO_2$ capture is under development consisting in $CO_2$ absorption by CaO [8-16]. The idea of the coal-based hydrogen production and $CO_2$ capture in a single step is presented in Figure 1.

In the process coal is gasified in a presence of calcium oxide at 600÷700°C and under the pressure of 3 MPa [9].

The summary reactions may be presented as follows:

$$C + 2H_2O + CaO = CaCO_3 + 2H_2 \quad \Delta H_{700} = -69.420\ \text{kJ/mol} \qquad (10)$$

Calcination reaction used to produce CaO and regenerate it for cyclic application should also been taken into account in a heat balance of the process:

$$CaCO_3 \rightarrow CaO + CO_2 \quad \Delta H_{900} = 166.786\ \text{kJ/mol} \qquad (11)$$

Other materials ($CaOSiO_2$, MgO) have also been tested as $CO_2$ sorbents in the process but it was calcium oxide which was proved to produce gas of the best quality and highest volume ($H_2$ 75%, $CH_4$ 24%) [17].

Table 1

Selected $CO_2$ storage sites operated or planned [19-25]

| **Location, reservoir name and process type, scale** | **Injection start [year]** | **Average injection rate [ton of $CO_2$/d]** | **Total planned storage [ton of $CO_2$]** |
|---|---|---|---|
| Fenn Big Valley, Canada, ECBM, pilot | 1998 | 50 | 200 |
| Sleipner, Norwey, Utsira saline formation, commercial | 1996 | 3,000 | 20,000,000 |
| Weyburn, Canada, EOR, commercial | 2000 | 3,000÷5,000 | 20,000,000 |
| Minami-Nagoaka, Japan, aquifier, gas filed, demonstration | 2002 | 40 | 10,000 |
| Recopol, Poland, ECBM, pilot | 2003 | 1 | 10 |
| Qinshui Basin, China, ECBM | 2003 | 30 | 150 |
| Yubari, Japan, ECBM, demonstration | 2004 | 10 | 200 |
| In Salah, Algeria, depleted gas field, commercial | 2004 | 3,000÷4,000 | 17,000,000 |
| Frio, USA, saline formation, pilot | 2004 | 177 | 1,600 |
| K12B, the Netherlands, EGR, demonstration | 2004 | 100 | 8,000,000 |
| Salt Creek, USA, EOR, commercial | 2004 | 5,000÷6,000 | 27,000,000 |
| CSEMP, canada, ECBM, pilot | 2005 | 50 | 10,000 |
| Pembina, Canada, EOR, pilot | 2005 | 50 | 50,000 |
| Teapot Dome, USA, EOR, demontration | 2006 | 2,600,000/year | |
| Snohvit, Norway, saline formation | 2007 | 1900 | 23,000,000 |
| Ketzin, Germany, saline formation | 2008 | 100 | 60,000 |
| Otwey, Australia, saline formations and depleted gas field, demonstration | 2008 | 126,5 | 100,000 |
| Gorgon, Australia, saline formation | planned for 2009 | 10,000 | 120,000,000 |
| Belchatow, Poland, onshore saline aquifiers, commercial | planned for 2015 | - | over 500,000 |

In summary, $CO_2$ concentration from the post-combustion process (13÷15% vol. in coal-fired systems and 3÷4% vol. in gas-fired turbines) and pressure is low, which implies the need for treatment of high volumes of gas and impurities such as particulate matter, $SO_2$ and $NO_x$ present in flue gas degrade sorbents. The pre-combustion and oxy-combustion processes utilize air separation units to combust coal in an oxygen-enriched environment, but the amount of oxygen required in oxy-combustion is significantly higher than in the pre-combustion process, increasing $CO_2$ capture costs.

In the pre-combustion process $CO_2$ stream is much more concentrated than in the post-combustion flue gas, and less oxygen is required in comparison with the oxy-combustion process, which makes the $CO_2$ capture less expensive. At present, however, there are few gasification plants in full-scale operation and capital costs are higher than for PC plants [6, 18].

Captured $CO_2$ can be commercially utilized for enhanced oil and gas recovery or for enhanced coal bed methane recovery from deep unminable coal seams.

The $CO_2$ storage capacity is estimated to be on the levels of 675÷900, 3÷200, 1,000÷10,000 $GtCO_2$ for oil and gas fields, unminable coal seams and deep saline formations, respectively [19]. The first industrial-scale $CO_2$ storage was started at Sleipner gas field in the North Sea (Norway), where compressed liquid $CO_2$ separated from methane is injected into a deep saline aquifer below the sea bed. In Table 1 selected $CO_2$ storage sites operated or planned are listed [19-25].

## Role of coal in energy mix of Poland

Poland is listed among the major world coal producers. Its energy system depends heavily on coal with 58% of electricity generated on hard coal and 32% on lignite (data for 2007) [26], while as much as 70% of natural gas and 95% of crude oil is imported [27]. Polish proved reserves of crude oil in 2007 amounted to 0.096 billion bbl and of natural gas 5,820 billion cubic feet [28].

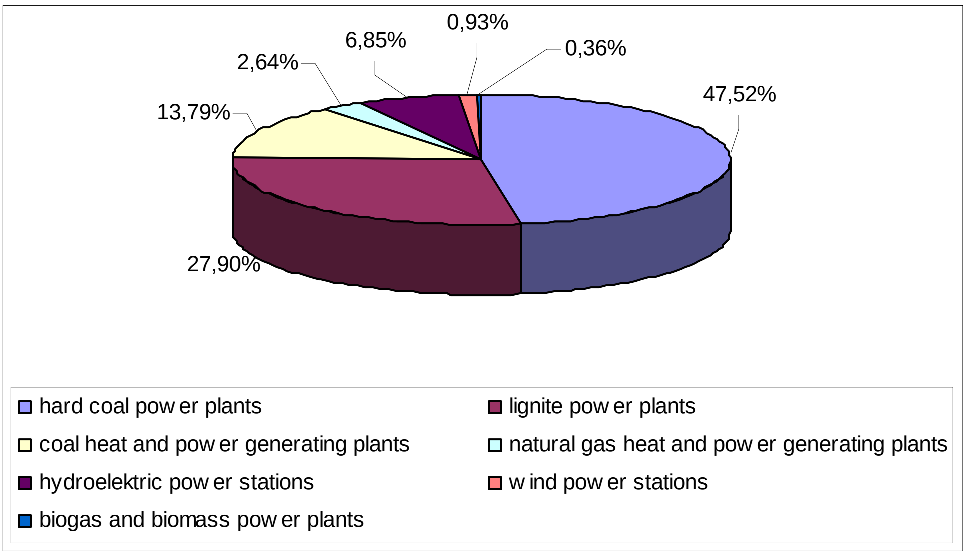


Fig. 2. Total installed electricity capacity for Poland (2008) [26]

The production, consumption and capacity of electricity generation in Poland in years 1998-2008 are given in Figures 2 and 3. The total installed electricity capacity in Poland in 2008 was 35,850 GW. The prognosis of power generation structure up to 2020 is given in Figure 4. The total electricity generation is expected to amount to 128.7, 140.10 and 156.10 TWh in years 2010, 2015 and 2020, respectively [26].

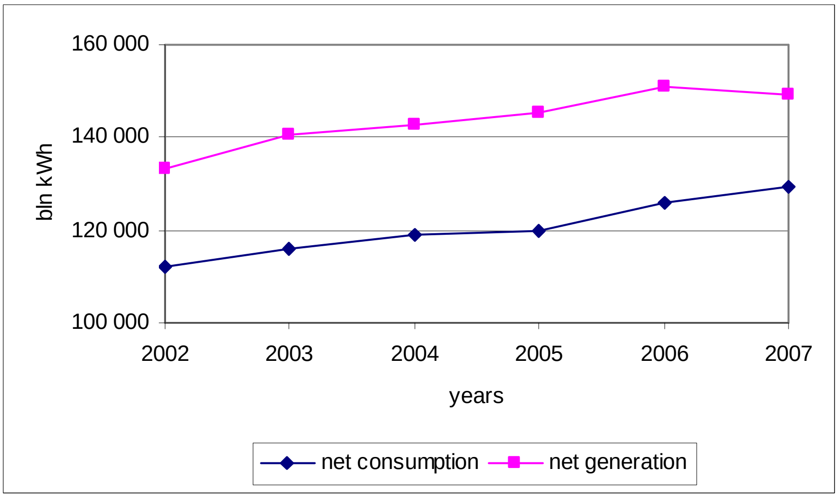


Fig. 3. Net electricity generation and consumption in Poland (2002-2007) [5]

The investments in Polish energy system planned for the next ten years are given in Table 2.

Table 2

The planned investments in Polish energy system [26]

| **Company** | **Location** | **Capacity [MW]** | **Start date (year)** | **Technology / Fuel** |
|---|---|---|---|---|
| Polska Grupa Energetyczna | Opole | 460 | 2012 | hard coal |
| | Opole | 460 | 2013 | hard coal |
| | Turow | 500 | 2014 | lignite |
| | Dolna Odra | 400 | 2016 | combined cycle gas turbine (CCGT) |
| | Dolna Odra | 400 | 2019 | CCGT |
| Poludniowy Koncern Energetyczny | Halemba | up to 440 | 2012 | hard coal |
| | Blachownia | 100÷200 | 2012 | hard coal or coke oven gas |
| | EC Bielsko-Biala | 100 | 2012 | hard coal |
| Vatenfall | Vatenfall Heat Poland Warsaw | 400 | 2013 | hard coal |
| CEZ | Skawina | 600÷1,000 | 2014 | hard coal |
| Polish Power | Zarnowiec | 1,600 | 2013-2014 | hard coal (gasification) |

As can be seen their majority are coal-based plants, which comes as no surprise, taking into account the domestic fossil fuel resources and energy police principles specified below.

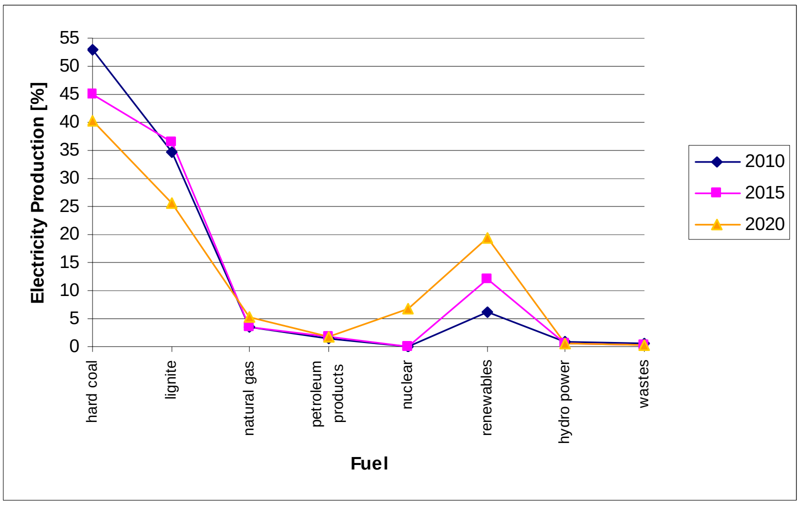


Fig. 4. Prognosis of electricity generation structure by fuel in Poland [26]

The documented balance resources of hard coal in Poland are estimated on the level of 43 201 million tons (31.12.2008) with 75% of steam coals and 25% coking coals (see Table 3). The resources located in operating deposits constitute 37.2% of the balance resources and amounts to 16,082 million tons. The resources are located in three basins with the largest being the Upper Silesian Coal Basin (Gornoslaskie Zaglebie Weglowe - GZW) with the area of 5,800 $km^2$ and over 78% of total domestic hard coal deposits, of which 19% are classified as exploited, 24% reserve and 27% prospective.

Table 3

Hard coal resources in Poland (2008) [29]

| | No. of deposits | Geological resources [million tons] | | Industrial |
|---|---|---|---|---|
| | | balanced | off balance | |
| **Total** | **138** | **43,201** | **24,667** | **4,338** |
| of which resources of exploited deposits: | | | | |
| Operating plants | 47 | 16,082 | 8,464 | 4,166 |
| of which resources of off balance deposits: | | | | |
| Total | 50 | 26,493 | 12,291 | 171 |
| 1. Deposits explored | 37 | 13,569 | 5268 | 171 |
| 2. Deposits pre-explored | 13 | 12,923 | 7,023 | - |
| of which resources of abandoned deposits: | | | | |
| Total | 41 | 626 | 3,922 | - |

The Lublin Coal Basin (Lubelskie Zaglebie Weglowe - LZW) covers the area of 9,100 $km^2$ with 21.5% of the total domestic hard coal deposits of which only 0.8% are exploited, 10% reserve and the majority - prospective. The identified and exploited deposits of the Lower Silesian Coal Basin (Dolnoslaskie Zaglebie Weglowe - DZW), abandoned for technical and economic reasons, are placed in the area of 350 $km^2$ and amounts to about 150 million tons.

The documented balanced lignite reserves in the total amount of 13,563 million tons are located in Belchatow, Turow, Patnow and Adamow [29]. The levels of geological and industrial lignite resources are given in Table 4.

Table 4

Lignite resources in Poland (2008) [29]

| | No. of deposits | Geological resources [million tons] | | Industrial |
|---|---|---|---|---|
| | | balanced | off balance | |
| **Total** | **77** | **13,5623** | **4,599** | **1,371** |
| of which resources of exploited deposits: | | | | |
| Total | 13 | 1,744 | 104 | 1,371 |
| 1. Operating plants | 12 | 867 | 90 | 751 |
| 2. Plants under construction | 1 | 877 | 14 | 620 |
| of which resources of off balance deposits: | | | | |
| Total | 59 | 11,810 | 4,491 | - |
| 1. Deposits explored | 29 | 2,791 | 715 | - |
| 2. Deposits pre-explored | 30 | 9,019 | 3,776 | - |
| of which resources of abandoned deposits: | | | | |
| Total | 5 | 9 | 4 | - |

## The principles of Polish Energy Policy by 2030

The primary directions of Polish energy policy until 2030 include strengthening the fuels and energy supplies security, improvement of energy efficiency and mitigation of the hazardous environmental impact of power industry. In the light of unquestionable leading role of coal in domestic energy mix and limited potentiality for import of liquid and gas fuels and electricity (up to 10%) the energy and fuels supplies security is defined as ensuring stable supplies to meet domestic needs at acceptable prices and with optimal use of own resources, that is coal as the main fuel for power industry. The meaning of diversification of liquid and gas fuels supply was widened and now takes into account not only diversification of supply directions but also diversification of technologies. The latter one refers to a development of coal-based technologies of liquid and gas fuels production. Meeting the expected increasing demand for electricity by creation of new generation capacity is to be performed using low-emission technologies of coal-based energy generation to ensure meeting the required pollutants emission levels, including $SO_2$, $NO_2$, dust and $CO_2$, in line with climate protection and climate-energy package adopted by EU [30]. The reduction of $CO_2$ emission is to be performed to the extent technically feasible, while avoiding too strong dependence on imported fuels. The above mentioned technologies include coal gasification to synthetic natural gas (SNG) and coal liquefaction to liquid fuels as well as efficient coal-pretreatment technologies. Construction of new, highly efficient power generation units and cogeneration technology by 2020 is also declared among the policy objectives. CCS technologies are planned to be implemented to enhance fuel recovery in gas and crude oil extraction. New ways of $CO_2$ industrial utilization are to be subject of R&D activities in terms of CCS development. At least two demonstration CCS installations are expected to be located in Poland. The electricity transmission system is to be modernized and extended to enable cross-border exchange of at least 15% by 2015 and 25% by 2030 of electricity used. But at the same time independence in terms of electricity and heat generation is expected to be maintain based almost entirely on domestic coal resources.

The preparatory works in terms of legal, social acceptance and technical aspects of nuclear energy systems are to be undertaken. The renewable energy production in Poland nowadays takes place mainly in small local power generation units and for local users. An increase in renewable energy sources in the final energy use to the level of 15% in 2020 and 20% in 2030 and biofuels in the transport fuels market to 10% by 2020 is, however, to be strongly supported.

The importance of CCT should therefore be recognized, especially in countries with the energy systems dependent on coal and commitments in terms of international activities aiming at sustainable development and GHG emission reduction in particularly. The technical advances within CCT development can not be achieved without partnership and cooperation between enterprises and local governments as well as between companies and scientific and research communities. Creation of the Innovative Silesian Cluster of Clean Coal Technologies, constituting the platform for R&D and policy activities, aimed at promotion of such wide cooperation in terms of CCT development in Poland [31].

## Summary and conclusions

The Clean Coal Technologies are of special interest and importance in the light of increasing energy demand and stable role of coal in ensuring energy security. The focus of CCT development has changed and nowadays the efforts in this regard are more devoted to optimization and implementation of highly efficient, zero-emission coal-based power generation technologies. The importance of CCT development, as a part of sustainable energy system, is recognized worldwide as over 40% of continuously increasing electricity demand is and will be generated in coal processing systems. Considerable financial support is secured for R&D projects worldwide within national and international programs.

The need for undertaking intensive activities in the field of CCT is also acknowledged in Poland. This should come as no surprise considering the structure of Polish energy system, characteristics of domestic fossil fuel resources base as well as national commitments in terms of European climate package. Targets and means aiming at facilitating development of CCT are included in the Energy Policy for Poland by 2030. There is also a considerable level of know-how and expertise available from the R&D institutes and industry traditionally related to mining and power generation fields. Coordination and support of future and already undertaken efforts as well as cooperation between different stakeholders of research and development, scientific and industry circles have, however, to be ensured. Some activities in this regard have already been initiated.

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## PRZYJAZNE ŚRODOWISKU TECHNOLOGIE PRZETWÓRSTWA WĘGLA DLA ZRÓWNOWAŻONEGO ROZWOJU POLSKIEGO SEKTORA ENERGETYCZNEGO

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**Abstrakt:** Według analityków, światowa produkcja energii elektrycznej wzrośnie z $18{,}0 \cdot 10^{12}$ kWh w 2006 do $31{,}8 \cdot 10^{12}$ kWh w 2030. Udział węgla jako surowca do produkcji energii elektrycznej pozostaje największy od lat i w roku 2030 ma osiągnąć 43%. Ocenia się, że z uwagi na najbogatsze zasoby i konkurencyjność rynkową dostępne zasoby węgla mogą zaspokoić światowe zapotrzebowanie na energię w perspektywie około 120 lat przy obecnym poziomie zużycia. Istnieje jednak konieczność doskonalenia technologii produkcji energii z wykorzystaniem węgla w zakresie ich sprawności i oddziaływania na środowisko. Tak zwane czyste technologie węglowe (CTW) umożliwiają wysoko sprawne i przyjazne środowisku użytkowanie węgla i obejmują: technologie wzbogacania węgla, poprawy sprawności istniejących elektrowni węglowych, zaawansowane technologie produkcji energii elektrycznej, technologie zeroemisyjne oraz technologie transportu i składowania $CO_2$. W pracy przedstawiono przewidywaną rolę węgla w energetyce ze szczególnym uwzględnieniem polityki energetycznej Polski oraz główne tendencje w zakresie technologii przetwarzania węgla w aspekcie czystych technologii węglowych.

**Słowa kluczowe:** węgiel, przetwarzanie, energia