Technical and economical conditions of new technologies that use coal

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Introduction

The development of new coal technologies is not only connected with the expectations of replacing fossil fuels by gaseous and liquid products derived from coal, but with the possibility of achieving better economic efficiency in the conditions of more stringent environmental requirements.

Both in power and chemical technologies significant amount of carbon dioxide is emitted, what is considered as the main reason of global warming. On one hand, fear of a crisis in access to crude oil and natural gas, and on other hand the requirements to reduce carbon dioxide emissions in power plants caused that one of the fundamental processes of chemical processing of coal - gasification - has become of interest both for the chemical industry and for power industry. The greatest activity in the industrial use of coal gasification is in China and the United States. In China alone about 100 million tons of coal is gasified annually, mainly for the requirements of chemical industry. The structure of primary fuels consumption in China is almost the same as in Poland, thus we can expect that a similar approach to the development of coal processing industry will be also attractive in Poland.

Classification of reactors used in gasification

Designs of reactors used in gasification can be divided into three main groups depending on type of fuel flow in the reaction zone [1÷3] (Fig. 1):

• reactors with moving bed
• reactors with fluidized bed
• reactors with entrained flow.

Other types of gas reactors are based on rotary kilns or on the liquid metal bath, but they are not used on an industrial scale so far. Gasification can also be carried out in situ in the coal seam (so-called underground gasification), though there are no industrial solutions yet [2].

The development of state-of-the-art gasification technology is first of all associated with the intensification of the process that is why fluidized bed and entrain flow reactors, enable obtaining high coefficient of heat and mass transfer and minimizing the content of tar substances in the processing gas, are considered to be prospective.

From the gasification technologies, carried out in fluidized bed and flow reactors definitely the latter ones are better developed and verified in a commercial scale, what can be proved by information collected from the currently operated gasification installations and from the installations planed for implementation [4, 5].

In the entrained flow reactors the pulverized coal and other fuels are supplied to the reaction zone in a mixture with oxygen and steam. The fuel can be supplied in a dry form (typically using nitrogen as the carrier) or as the water suspension. The reactors operate normally in temperature range from 1200 to 1600°C under the pressure 2÷8 MPa (most of the commercial installations operate at pressure 2.5 MPa). Short residence time (few seconds) of gas in the reaction zone enables obtaining high capacity, but it requires pulverization of fed fuel to grain size below 0.1 mm. Entrained bed reactors are very flexible as regards changes in characteristics of used fuels, what makes use both solid and liquid fuels possible. High temperature of gasifying flame core, when exceeding ash pour point, ensures high degree of conversion and lack of tar contaminants in the produced gas.

State of art of commercial gasification technologies

Review of world advance in gasification technology, made by US Department of Energy and National Energy Technology Laboratory [4, 5] indicates that 144 gasification installations equipped with 427 reactors of total power 56 238 MWth (thermal power in produced gas) are in operation. It means that within the years 1980 ÷ 2007 over triple increase of world production of gas obtained by this method (from about 20 to 56 GW) was reported. Within the years 2004-2007, i.e. from the previous review of DOE/NETL, 27 new gasification installations were started up (11 237 MWth; increase by 25%). That concerns mainly coal gasification systems that produce gas for the chemical syntheses located in China. Further 41% increase will be reached at the end of 2010 (Fig. 2) [4, 5, 8]. Till 2010 the highest increase of production capacity of gasification installations was reported in Africa and Near East, but it concerns the systems for natural gas conversion implemented in Qatar of total power in produced gas 11 000 MWth (47% of planned increase of world gas production), which will be part of installation for production of liquid fuels. The second place will be taken by the Asia/Pacific region (46% increase of gas production), mainly due to coal gasification installations implemented in China [4, 5, 8]. About 100 million tons of coal per year is gasified in China, mainly to meet demand of chemical industry. Basing on gasification of 70% of produced ammonia (total production 46.8 mln t/y) and 80% (total production 11.0 mln t/y). Five installations of methanol synthesis from coal gas have been started up within last two years. At present 60 Texaco reactors and 20 Shell reactors are in operation.

Fig. 1. Solutions of reactors used for gasification [1÷3, 6, 7]

![Fig. 1. Solutions of reactors used for gasification](image)

Fig. 2. World progress in technology of fuels gasification [5, 8]

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Published DOE/NETL review includes such a solution to the gasification technology. In fact, it is a process of semi-burning of natural gas carried out at high pressure in the system of Shell gasification reactor.

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Raw material for gasification [5, 8]

Coal is the main feed raw material used in gasification installations (55% share in world production of gas). Next place of feed is taken by by-products from the petrochemical industry (33%) and the rest 12% is produced from gas, petrol coke and biomass. In the case of planned installations (till 2010) role of coal as the basic fuel will be maintained. It will be used in 12 from 15 constructed plants.

Among the installations currently operated for the chemical industry (except Fischer-Tropsch synthesis) by-products of petrochemical industry are the main feed raw materials (48% of gas production). Next places of feed are taken by coal (38%), natural gas (13%) and petrol coke (1%). Share of coal in a production of syngas will increase up to 50% till 2010 (Fig. 3).

Coal gasification[^1] [5, 8]

**Directions of using the gas**

The gas produced in coal gasification systems is mainly used in the Fischer-Tropsch process (47% of world gas production). First of all it is associated with liquid fuels plants operating in South Africa, which use gasification technology in the fixed bed (Sasol Lurgi). The remaining 53% of the gas produced from coal is used for production of various chemicals (including ammonia, hydrogen, methanol and other oxygenates, 32%), electric power (14%) and gaseous fuels (7%). For installations planned to be launched in 2008-2010, the generated gas will be used mainly for the production of chemicals (72%; Fig. 4).

**Used technologies**

Technologies of gasification in reactors with fixed bed (that are not under development now) are the most popular (57% of gas production), what results from a high production potential of Sasol factories. However, when considering the planned startups share of that technologies will drop down significantly (to 42%). The processes that use the reactors with entrained flow are most intensively developed now. That can be confirmed by already finished implementation of technology in the years 2004-2007 and by those that are planned to be launched till 2010; practically all of them concern the reactors of such a design.

When considering only the technologies of coal gasification in reactors with entrained flow (technologies with the greatest potential for development), the technologies of the following companies have dominant share of gas production: GE Energy/Texaco (42%) and Shell (40%). The other technologies are: Siemens Fuel Gasification Technology (SFG, 6%), ConocoPhillips/E-Gas (4.5%), Elcogas S.A./Prenflo (4.5%), Mitsubishi (3%). Shell technology (50%) and Siemens/SFG technology (40%) belong to those processes that are dominating in the installations that are planned to be launched (Fig. 5).

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[^1]: Due to technological similarity of the systems using coal and coke, presented data concern the installations using both fuels (share of petrol coke for operating and for planned installations is 4.5% and 7.7% respectively).
Power generation – IGCC systems

The concept of integrated gas-steam system (IGCC) consists in gasification of coal to gas fuel of medium caloric value, which is burnt in the gas turbine after treatment. From waste off gases is used for generation of steam that drives the steam turbine. The most important components of the system are: air separation unit (ASU), gas pre-treatment unit, heat recovery steam generator (HRSG). Slag and sulphur or sulphuric acid are the by-products of IGCC system. Main advantages of IGCC system are as follows [3]:

- high efficiency of power generation
- high flexibility as regards fed fuel (e.g. different coal grades, residues and biomass) with a possibility of automatic switching to oil or natural gas
- low emission levels of hazardous dust and gas components.

In the 90’s of the last century 5 pilot installations generating power in combination with coal gasification were launched in the following power plants: Demkolec (Buggenum, Holland) — 252 MW, Tempa Electric (Florida, USA) — 250 MW, Wabash River (Indiana, USA) — 252 MW, Puertollano (Spain) — 300 MW, Pinon Pine (Nevada, USA) — 100 MW [3, 6, 9÷12]. State-of-the-art reactors used in them belong to the biggest coal units and are based on gas generation technologies of the following companies: Shell (Buggenum), entrained flow reactor; Prenflo (Puertollano), entrained flow reactor; E-Gas/Destec (Wabash River), entrained flow reactor; Texaco (Tampa Electric), entrained flow reactor; KRW (Pinon Pine), fluidized bed reactor.

Four of them i.e. Demkolec (Buggenum, Netherlands), Tempa Electric (Florida, USA), Wabash River (Indiana, USA), Puertollano (Spain) after demonstration period have started commercial operation. Only the project Pinion Pine was failed and after demonstration period was stopped.

Apart of high efficiency of power generation, a possibility of removal of harmful substances from gas, including CO\(_2\), before burning process (pre-combustion capture) is very significant advantage of the IGCC systems. Smaller gas streams (higher concentration of contaminants) and the pressure higher than in the classical power systems (burning, exhaust gases treatment) enable obtaining high efficiency of contaminants removal at relatively low operational costs.

Necessity of CO\(_2\) separation from the power systems (EU directives) in combination with a possibility of CO\(_2\) capture from the gas before burning process makes the IGCC technology competitive in relation to the state-of-the-art steam blocks for supercritical parameters.

Relative costs of carbon dioxide capture and elimination of CO\(_2\) emission as well as power generation costs, when using the processes of carbon dioxide capture for different power generation technologies were given in Fig. 7 [13].

Production of liquid fuels using Fischer-Tropsch process

Fischer-Tropsch process was used for production of liquid fuels already in 1930ties. At present liquid fuels from coal are produced using F-T method in Sasol (South African Synthetic Oil Limitem) factories. The current advance in technology of production of liquid fuels from gas, generated in coal gasification process, has been achieved due to research activities in Sasol factories. Development of FT synthesis reactors resulted from the need to improve heat exchange – recovery of heat generated during synthesis as well as the need to increase conversion of reactants. Fig. 8 shows the basic types of reactors used for Fischer-Tropsch synthesis.

Dependence on the type of products we want to obtain, the FT synthesis can be carried out at low (180-240°C) or higher (300-350°C) temperature with cobalt or iron oxide catalyst. Synthesis temperatures are kept below 400°C to avoid excessive amounts of synthesized methane. Industrial (high volume) synthesis of liquid hydrocarbons is carried out on a composite iron oxide and cobalt catalysts, enriched with activators and stabilizers. In the case of the cobalt catalyst on a carrier - diatomaceous earth, which was widely used during World War II, in addition to cobalt, also the thorium and magnesium oxides are added. Commercial iron catalyst LP33/81 (Ruhrchemie), often used as the standard/reference catalyst for testing new catalytic compositions, has a nominal composition 100 Fe/5 Cu/4.2 K2SiO3.

Generally it can be assumed that the cobalt catalysts are used at low temperatures, as with temperature rise the methane production increases intensively. Low temperatures lead to a formation of high molecular weight hydrocarbons (waxes), from which diesel fuel is obtained after hydrocracking, while elevation of temperature directs the synthesis towards gasoline hydrocarbons and olefins products. To direct the synthesis to gasoline hydrocarbons it is preferred to use iron catalyst at high temperature in the fluidized bed reactor. In turn, for direction of the synthesis towards diesel hydrocarbons (diesel fuel), it is preferable to carry out synthesis in the water suspension reactor with cobalt catalyst. In the full technological cycle, the synthesis products are subjected to processing operations, which consist mainly of separation (distillation), and hydrocracking, hyroisomerization and reforming to obtain commercial products.
Hydrogen production from the gas obtained in coal gasification process

Hydrogen is currently produced on an industrial scale mainly by converting natural gas (reforming, semi-burning). In recent years, due to rising gas prices, hydrogen production using other materials including coal (through its gasification) became economically attractive. This is reflected in the newly built plants, mainly in China. Hydrogen gas, after complete conversion of carbon monoxide and decarburation, apart from hydrogen contains polluting substances (in amount even up to 10%): steam, carbon dioxide, carbon monoxide and traces of sulfur compounds.

In a situation, where the gasification process is carried out in a reactor with transportation of coal in a stream of nitrogen, the nitrogen is also a significant contamination, content of which reaches 5% in the hydrogen gas. To obtain hydrogen of high purity (over 99%), the produced hydrogen must be subjected to the enrichment process. On the industrial scale, the pressure swing adsorption (PSA), membrane (polymer) systems and cryogenic separation are currently used for enrichment of hydrogen from hydrogen-bearing gases. PSA Technology is the most widely used process in the refining industry (and in gasification systems).

The main advantages of the PSA technology in relation to others include: high purity of the obtained product, flexibility as regards changes in supplied gas composition, low pressure loss and cost effectiveness of gas production. It is currently the best technological option for typical conditions of coal gasification systems (high concentration of hydrogen, over 50%, high stream volumes and high pressure of process gas). The published analysis of potential possibilities for hydrogen production, integrated with coal gasification, where the process is a standard for hydrogen separation [17, 18], confirmed that.

PSA technology has high separation efficiency (for hydrogen it is over 90%), possibility of obtaining hydrogen of high purity > 99.9%, high ability of CO and CO₂ separation of, and high flexibility as regards fed gas composition [16]. PSA plants are characterized by low pressure losses. Investment costs and operating costs of these installations are relatively low. Porous zeolites binding all components of process gases, except hydrogen are used as adsorbents in the technology of hydrogen in the PSA systems. Activated carbons can also be used as adsorbent for hydrogen enrichment process.

The installation consists of a series of adsorbers (usually 4-6) operating periodically in adsorption and desorption cycles at ambient temperature and pressure 0.05-2 MPa.

Depending on adsorbers size, cycle duration in each apparatus varies from a few to ten or so minutes. At the final stage of desorption the adsorbent bed is purged with pure hydrogen.

Production of methanol from the gas obtained in coal gasification process

Beginnings of methanol synthesis are associated with experiments of hydrogenation of carbon monoxide carried out in Germany by Mitschach, Weitzel, Pier, Luther, and Rumpf from BASF. In Poland, research work on methanol synthesis from carbon monoxide and hydrogen was carried out during interwar period by Professor Blasiak, who developed the catalyst (CuO-Zn-Al₂O₃), yet widely used. This catalyst is used in temperature 220-275°C and a pressure of 50-100 bar, is very stable and under normal operating conditions its life is 3-5 years [19 ± 21].

Production of formaldehyde, acetic acid and acetic anhydride, methylvamine, methyl chloride, and solvents is the most important direction of methanol use. Methanol can also be used directly as a motor fuel and can be added to motor fuels of crude oil origin, to improve their operational parameters (MTBE, methyl tert-butil ether). Moreover, processes of direct production of motor fuels from methanol (MTG - methanol to gasoline, and MOGD - methanol to gasoline and diesel) are used on an industrial scale. New technologies of generation of ethylene and propylene from methanol (MTO - methanol to olefins) [19] are being developed. Methanol has also become a leading fuel used in cells, which are under continuous development.

By 2002, almost entire world production of methanol (90%) was based on synthesis gas from natural gas. Most of the newly launched systems use different raw materials, first of all coal [19 ± 21]. During the past 20 years all the methanol factories in Poland were closed down, and all demand for methanol in Poland is covered by import, mainly from Germany and Russia. The estimated demand for methanol for the chemical industry and for wood-based panels in 2007 reached 380 thousand tons. It is expected that by 2015 demand will rise up to 520 thousand tons per year [22].

Synthesis of methanol from the synthesis gas takes place at high temperature and high pressure. The following ratio in the composition of synthesis gas is preferred for proper reaction progress: (H₂ - O₂)/ (CO + CO₂) = 2.

Although the methanol is produced first of all from H₂ and CO, the admixture of CO₂ in the synthesis gas in amount of 4-8% accelerates the synthesis reaction rate (by about 100 times.) Carbon dioxide is adsorbed on the catalyst’s oxidized surface forming a transitional system Cu/CuO * CO₂, which is reduced by hydrogen to methanol and water. Very good catalyzing properties of copper in the case of CO conversion, cause that generated water reacts with CO contained in the gas and reproduces CO₂ that has reacted.

Thermodynamics limitations of methanol synthesis process cause that the degree of conversion of syngas to methanol is about 25%. Higher capacity can be achieved by lowering the temperature of the process, but this is associated with a simultaneous decrease of catalyst activity. To overcome this barrier, in industrial systems the synthesis reactors operate in a circulation system, in which, the produced methanol is removed from the gas led out from the reactor after cooling and the unconverted part of the gas is mixed with fresh gas and recycled to the reactor after the compression and heating. In such a way 99% conversion of synthesis gas can be achieved. In such a circulation system the amount of gas entering the synthesis reactor increases by about 3.8-4.0 times comparing to the amount of fresh gas fed to the synthesis.

Synthesis of methanol is an exothermic process, requiring carrying away large amount of heat from the reaction zone, the problem is solved already at the stage of fusion reactor designs [19 ± 24]. The following methanol synthesis reactor designs are used:

- adiabatic reactor with synthesis gas injection
- isothermal tubular reactor with steam generation
- tubular reactor with internal cooling
- reactor with external intersectional cooling.

A three-phase slurry reactor, in which the catalyst is suspended in a mineral oil, through which the syngas is bubbled, is the latest and developmental solution. A heat exchanger cooling the reaction environment is placed in this suspension [25 ± 27]. The solution is currently at the stage of pilot testing and demonstration; it has not been applied in industry so far (currently the only working system is located in the Eastman Chemical Corporation plant in Kingsport, USA and has a capacity of only 230 t/day).

Polygeneration power plant

Operation of polygeneration systems consists in a simultaneous production of chemical products and electric power (and heat) from the synthesis gas. Maximal utilization of chemical energy of synthesis gas i.e. obtaining highest possible total power efficiency of fuel transformation into useful products at lowest investment and operating costs is the aim of such systems. At present power production systems integrated with the production of hydrogen, methanol and products using Fischer-Tropsch process, belong to the commonly used polygeneration systems.
An example of polygeneration option is the project “Power Poly- 
generation” [28], planned for implementation by the Southern Poland 
Power Company and Kędzierzyn Nitrogen Plant SA (Zakłady Azotowe 
Kędzierzyn), considered as one of the potential directions of power re-

storation in Poland that makes a platform for the development of new 
“clean” coal technologies in the power and chemical industries.

The planned installation will consist of two main modules, i.e. che-

mical module (production of synthesis gas) and power module (IGCC 

system). Hard coal (annual consumption of 2 million tons) produced in 

the Upper Basin will be the basic fuel supplying gasification installation 

and the power unit. Schematic diagram of demonstration installation 
of polygeneration power plant is shown in Figure 9.

**CCS demonstration system**

In the basic technological variant the installation will consist of:

- system for coal gasification (A1, Fig. 9), equipped with the process 
gas conversion and cleaning installations, with CO₂ separation 
system (A2, Fig. 9) producing synthesis gas for the chemical 
industry and high pressure steam for power and heat generation 

- system for coal gasification (B1; Fig. 9) integrated with the 
system of gas-steam turbines (B3, IGCC; Fig. 9) equipped with 
the synthesis gas conversion and cleaning installations, with CO₂ 
pre-combustion capture system (B2; Fig. 9), generating electric 

power.

Gasification reactors, working in the demonstration system, due 
to the same capacity, may be a reserve to each other, increasing 
(depending on the accepted production schedule) annual availability 
of syngas or electric power production nodes. High-pressure steam 
generated in the synthesis gas production system (A, Fig. 9) will supply 
a steam turbine of a typical heat and power plant (not included in Fig. 
9). Consequently, this will enable reduction of coal consumption and 
CO₂ emission in the systems not equipped with carbon dioxide capture 
systems.

Electric power of IGCC system will be 309 MWe. Finally 2 221 
thousand tons of CO₂ per year will be geologically sequestrated (to-

tal amount of CO₂ separated in the cogeneration production system 
of synthesis gas and power, Fig. 9). The synthesis gas in quantities of 
703 thousand tons per year will give 529 thousand tons per year of 
syngas or electric power production nodes. High-pressure steam 

generated in the synthesis gas production system (A, Fig. 9) will supply 

a steam turbine of a typical heat and power plant (not included in Fig. 
9). Consequently, this will enable reduction of coal consumption and 
CO₂ emission in the systems not equipped with carbon dioxide capture 
systems.

![Fig. 9. Schematic diagram of polygeneration power plant](image)

**Analysis of the ability to implement the technology of fuels 
production from coal in the Polish conditions**

Presented results have been obtained within the project entitled: 
“Feasibility study of the installation for production of gaseous and liquid 
fuels from coal”, prepared for the Polish Ministry of Economy [22].

Three variants of technology: Variant I - the installation for pro-
duction of liquid fuels; Variant II - the installation for production of 
hydrogen; Variant III - the installation for production of methanol, were 
analyzed.

It was assumed that the gasification process will be realized in the 
reaction system of capacity of a single gasification reactor equal to 125 
t/h of coal in the raw state: this amount is within the range of the real 
processing capacity – of currently operated and the newly designed 
stream gasification reactors – that generally is within the range from 
100 to 130 t/h of coal.

Scale of coal processing for the considered variants was based on 
an analysis of demand for each product and technical limitations as-

sociated with their distribution (hydrogen). Polish stony coals of class 
18-20 were assumed for the calculation. Time of operation equal to 
85% of annual working time, i.e. 7446 hours per year was assumed 
for all variants.

In Table 1 summary of the results in a form of consumption volume 
and production volume for the analyzed production systems (selected 
streams) were given.

<table>
<thead>
<tr>
<th>Item</th>
<th>Name of stream</th>
<th>Variant I</th>
<th>Variant II</th>
<th>Variant III</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Liquid fuels</td>
<td>t/y</td>
<td>t/y</td>
<td>t/y</td>
</tr>
<tr>
<td>1</td>
<td>Coal</td>
<td>5 584 500</td>
<td>930 750</td>
<td>930 750</td>
</tr>
<tr>
<td>2</td>
<td>Water</td>
<td>13 691 407</td>
<td>2 613 546</td>
<td>2 058 536</td>
</tr>
<tr>
<td>3</td>
<td>Propane butane</td>
<td>108 563</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>4</td>
<td>Diesel oil</td>
<td>188 235</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>5</td>
<td>Semi product to diesel oil</td>
<td>791 808</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>6</td>
<td>Hydrogen</td>
<td>-</td>
<td>81 467</td>
<td>-</td>
</tr>
<tr>
<td>7</td>
<td>Methanol (AA class)</td>
<td>-</td>
<td>-</td>
<td>462 680</td>
</tr>
<tr>
<td>8</td>
<td>Sulphur – trade product</td>
<td>49 144</td>
<td>16 225</td>
<td>16 225</td>
</tr>
<tr>
<td>9</td>
<td>Carbon dioxide</td>
<td>6 579 732</td>
<td>1 403 184</td>
<td>930 914</td>
</tr>
<tr>
<td>10</td>
<td>Solid product from gasification</td>
<td>1 114 815</td>
<td>174 207</td>
<td>210 819</td>
</tr>
</tbody>
</table>

- It was assumed that not processed product of FT synthesis is i.e. “substitute of crude oil” 
defined as “semi product to diesel oil” that will be processed - to obtain trade products i.e. 
diesel oil and eventually petrol – in other technological installations that currently exist or that 
will be constructed especially for that purpose (not included in the analysis), will be a part of 
installation’s final product.

Financial analyses and sensitivity analyses were made for the fol-

lowing scenarios:

- scenario 1 - basic one – planning realization of the project without 
necessity of purchasing emission allowances

- scenario 2 – reference one, in which after construction of the plant 
100 % emission allowances is bought

- scenario 3 – perspective one, which assumes building the installa-
tion for transportation and storage of CO₂

Investment expenditures of the project were determined on the 
basis of data from reports of American and European consulting firms, 
in particular, Worley Parsons Group Inc., EPRI, Bechtel Corp., Siemens, 
and on the basis of expertise, knowledge and experience of Polish de-

signing companies and from realization of investments (Tab. 1). The 
following key data and cost assumptions were accepted:
investment expenditures, presented as overnight costs \(^1\), on the basis of II quarter of 2006 considering average weighted increase of investment expenditures till mid-2008 by about 60% \(^4\). 
- cost of apparatus and equipment with starting amount of chemicals and catalysts 
- unplanned expenditures include costs of process and design risk.

### Table 2

<table>
<thead>
<tr>
<th>Investment expenditures</th>
<th>Cost, thousand PLN</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Variant I (F-T)</td>
</tr>
<tr>
<td>without CO(_2) sequestration (scenarios I and 2)</td>
<td>9 355 846</td>
</tr>
<tr>
<td>with CO(_2) sequestration (scenario 3)</td>
<td>9 792 234</td>
</tr>
</tbody>
</table>

A key measure of financial effectiveness, which is the internal rate of return (IRR) for the different variants, is presented in a diagram (Fig. 10). In the case of Version I (liquid fuel production) the required levels of return on capital in any of the planned scenarios are unavailable. The main reason is very high initial investment expenditure for the plant construction and starting up the production process. Version II - hydrogen production - enables return of capital costs, but in view of the requirement of compulsory purchase of CO\(_2\) emission rights it would be necessary to build additional installation for transportation and storage of carbon dioxide. In the case of its absence the project is not cost-effective. However, the situation, when the chemical industry will be charged for CO\(_2\) emission from reforming and conversion of natural gas, what causes a significant advantage of the solutions basing on coal gasification process, should also be taken into account. The methanol production (variant III) is the best solution, among the analyzed versions. Lack of effectiveness in scenario 2 for variant I and II as well as lower profits rate in variant III in relation to the scenario 1, confirm usefulness of CO\(_2\) transportation and storage, especially in a view of high probability of requirement for purchasing of all emission rights after 2012.

Specification of minimal selling price that ensure cost-effectiveness in the case of discussed variants was given in Table 3.

### Table 3

<table>
<thead>
<tr>
<th>Minimal selling prices</th>
<th>Variant I (F-T)</th>
<th>Variant II (hydrogen)</th>
<th>Variant III (methanol)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cost of crude oil barrel, USD</td>
<td>7 875.00</td>
<td>87.00</td>
<td>4 895.00</td>
</tr>
<tr>
<td>Cost of natural gas, PLN/coal-m(^2)</td>
<td>6 082.00</td>
<td>1 035.00</td>
<td>1 025.00</td>
</tr>
</tbody>
</table>

\* equivalent price of natural gas, when using this raw material in a production (steam reforming)

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