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WHY THERE IS A NECESSITY TO BUILD NUCLEAR POWER PLANTS IN POLAND?

1. Introduction – aim and contents of the paper

The aim of the paper is to show and to justify the advantages of nuclear power development for the society in Poland. The arguments presented in the paper, justifying the necessity to start the nuclear programme in Poland, are not only related to the energy balance, but also to economic and environmental features of the nuclear option.

The **energy** aspect is first of all the necessity to cover the increasing demand for electricity and to ensure the security of its supply, with increasing diversification of the fuels for power plants, particularly in the context of the growing domination of the main supplier of natural gas to Europe.

The **economic** aspect is the necessity to achieve a structure of the electricity sources which would assure the lowest generation costs in the conditions of limited potential of renewable sources of reasonable cost and growing environmental requirements.

The **environmental** aspect means not only the necessity to ensure a structure of electricity generation sources which allows for complience with the legally binding environmental requirements but also which allows a minimal level of the environment pollution at the given stage of the development of electricity generation technologies. This means the application of the ALARA principle (pollution As Low As Reasonably Achievable) which is, i. a., applied in the designing of nuclear power plants.

The paper presents forecasts of the electricity demand to 2030 for possible foreseeable scenarios of the economic development of Poland as well as the economically optimal structures of electricity sources for the expected environmental conditions. The prices of primary energy sources and the availability of investment financing are taken into account. In the optimising process, the following sources were considered: coal, lignite and gas fired power and CHP plants, under the assumption that Poland fulfills its obligations to develop renewable energy sources within the existing potential of these sources.

Additionally the external costs of electricity generation by different thermal and the nuclear plants were analysed. These costs comprise, among others, the costs of the health casualities caused by the combustion of organic fuels and the emission of air pollutants (SO_2, NO_x and particulates) as well as the consequences of the greenhouse effect caused by CO_2 emission. In relation to the nuclear sources the threats for the society and the environment caused by the nuclear plants operation and by the nuclear waste storage were evaluated.

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2. Present situation and the forecast of energy demand in Poland

2.1. Introductory remarks

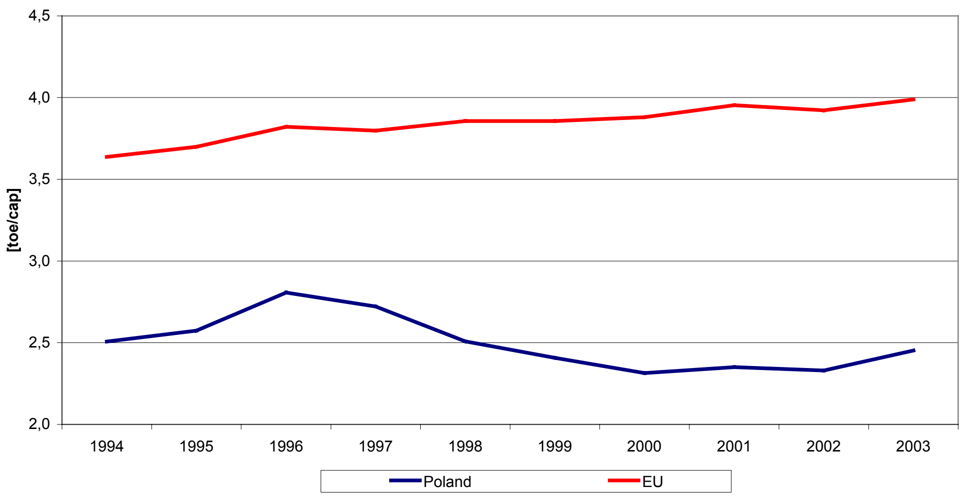
Justification of the nuclear power development requires the elaboration of the professional forecasts of electricity demand for the considered time horizon, within the given structure of final energy consumption, which depends on the features and the growth rates of the national economy.

The results of the analytical and prognostic study [6], prepared by the Energy Market Agency in cooperation with the International Atomic Energy Agency (IAEA) experts, were used in the present paper. In the study, the computer simulation models, reflecting both the economic sectors and the energy sector mechanisms, were applied.

2.2. Energy intensity and electricity intensity of economy in Poland and in the European Union 1990-2004

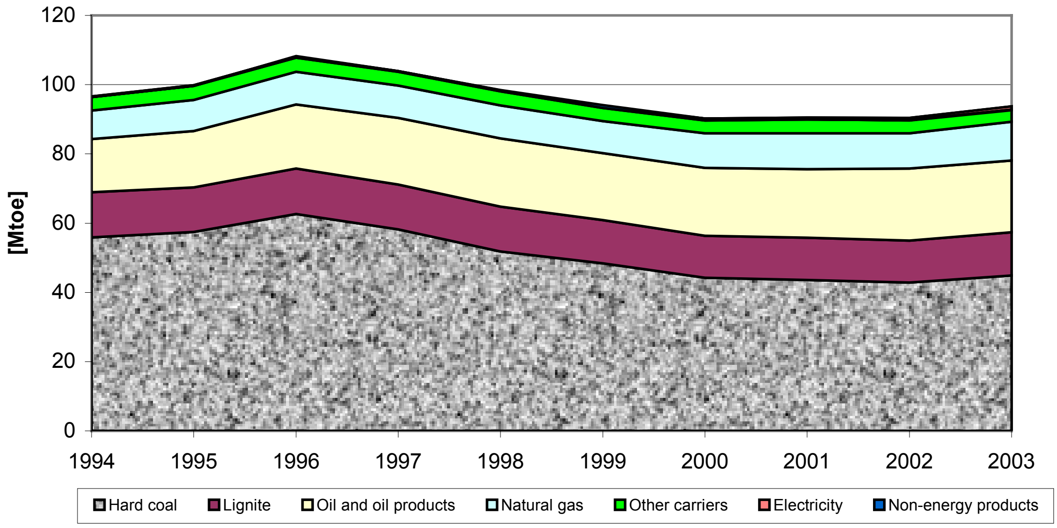
The forecasts of the electricity demand were based on the analysis of the present situation of energy consumption and on the comparisons with other countries. The European Union countries are the natural framework of reference for Poland. The comparisons of primary energy consumption and final energy consumption per capita and per unit of Gross Domestic Product are essential in this aspect. The consumption of electricity per capita and per GDP unit are the particularly important indicators characterising the level of economic development of the society.

In Poland, the annual average per capita consumption of primary energy has been maintained at almost constant level of approx. 2.5 toe over the recent 10 years, despite the growth of GDP, owing to the market oriented economic transformation. In the EU-15 the consumption of primary energy has been growing during this time and achieved approx. 4.0 toe per capita in 2003 (Fig. 1).



Source: IEA, OECD: Energy Balances of OECD Countries

Fig. 1. Primary energy consumption per capita in Poland and in EU-15



Source: Primary energy balances, Energy Market Agency

Fig. 2. Size and structure of primary energy consumption in Poland 1994-2003

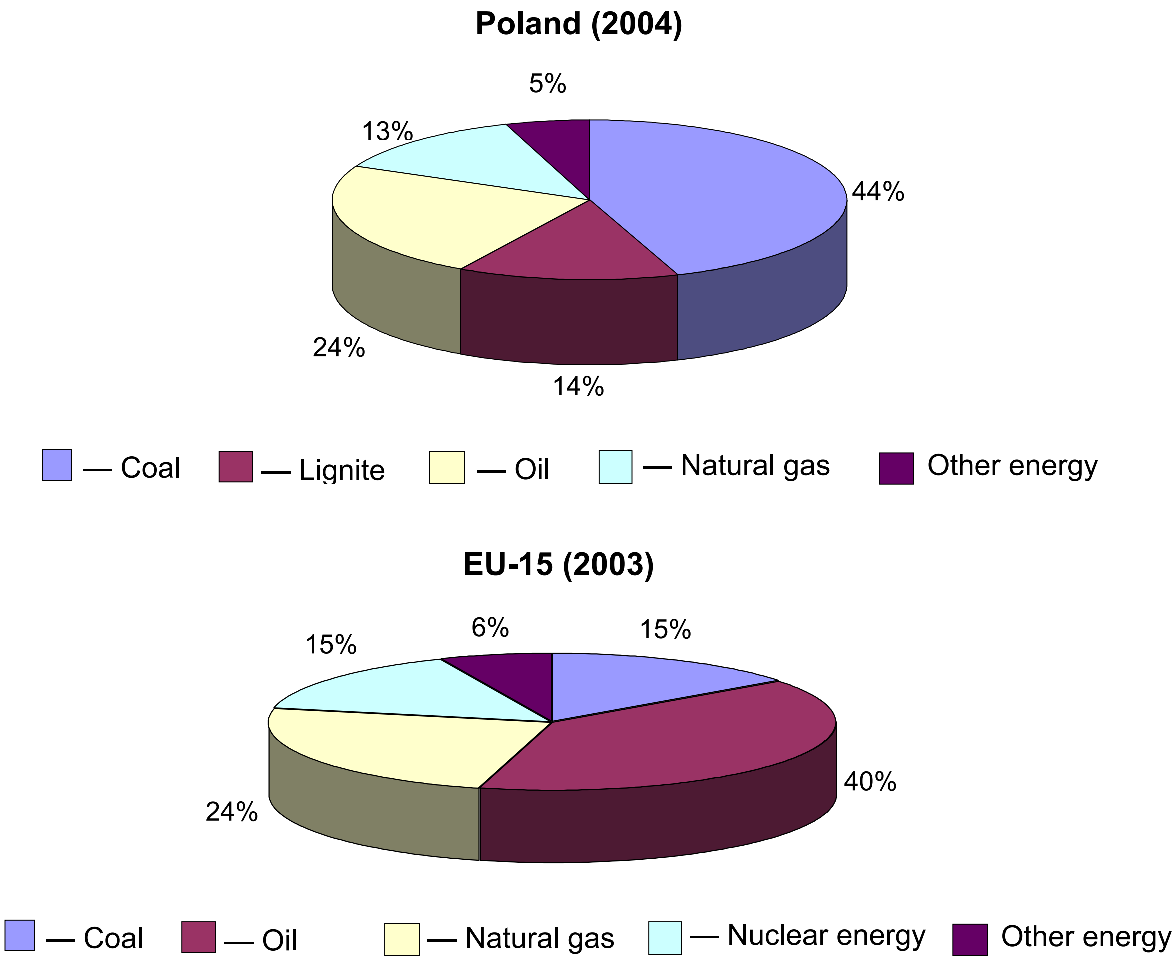
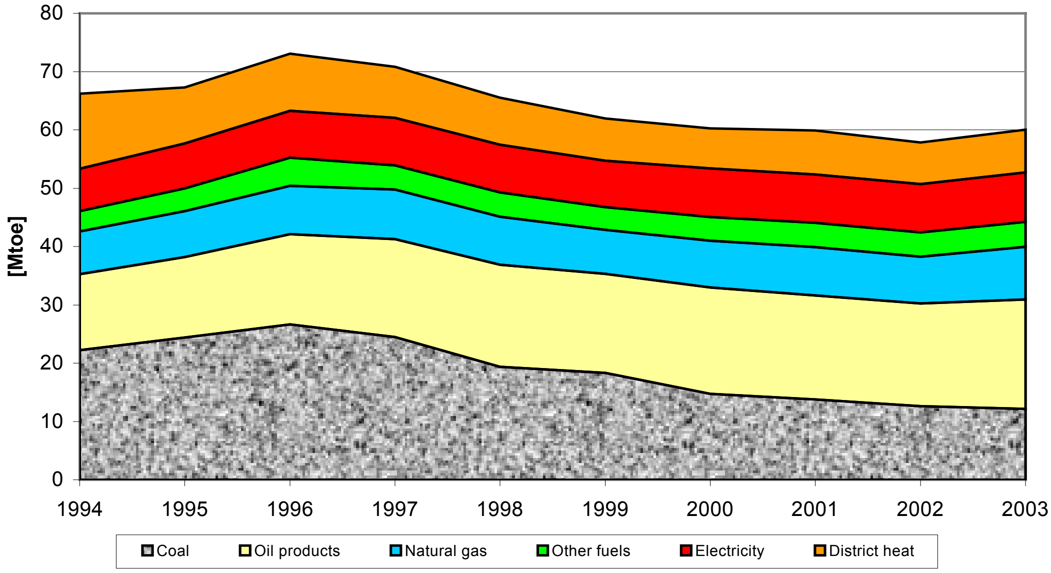


Fig. 3. Structure of primary energy consumption in Poland (2004) and in EU-15 (2003)

The structure of primary energy consumption is dominated by solid fuels in Poland (Fig. 3). This is the reason for the less efficient environmental performance of Polish energy sector in comparison with the European Union, particularly in the aspect of CO_2 emission.

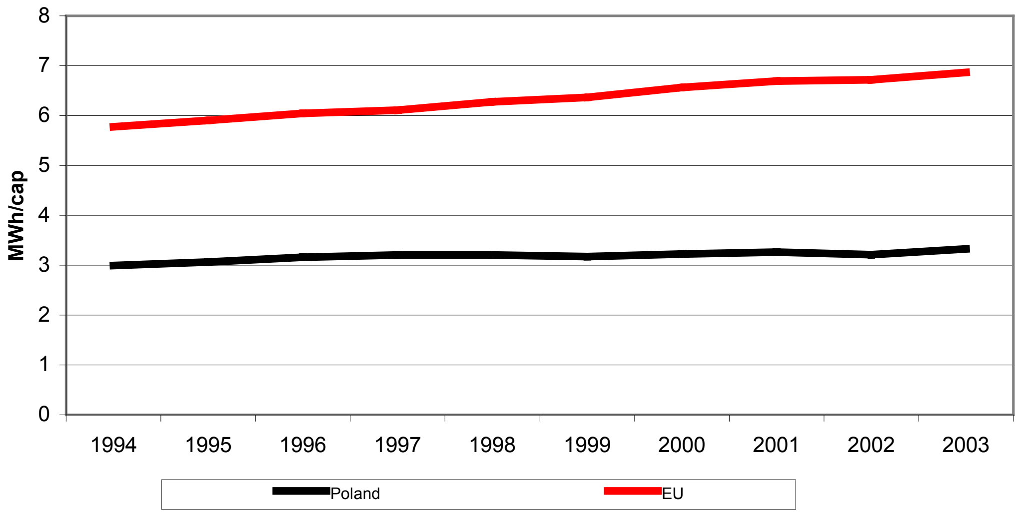
The energy intensity of Polish economy, expressed by the ratio of the primary energy consumption to the GDP in USD, calculated by the exchange rate, was four times higher than the EU average in 1994. In 2003 the same relation decreased to 2.8 times. This proves the large influence of the economic transformation on the improvement of the energy productivity and indicates that the further reserves of energy efficiency still exist.

The final energy consumption has also decreased in Poland after 1996 (Fig. 4), despite the economic growth, owing to the effects of transformation. Final energy consumption is however still composed of the low shares of the noble (highly efficient) energy commodities – electricity and natural gas, and relatively high share of the network heat, which is the specific feature of the Polish energy sector.



Source: Energy balances of Poland, Energy Market Agency

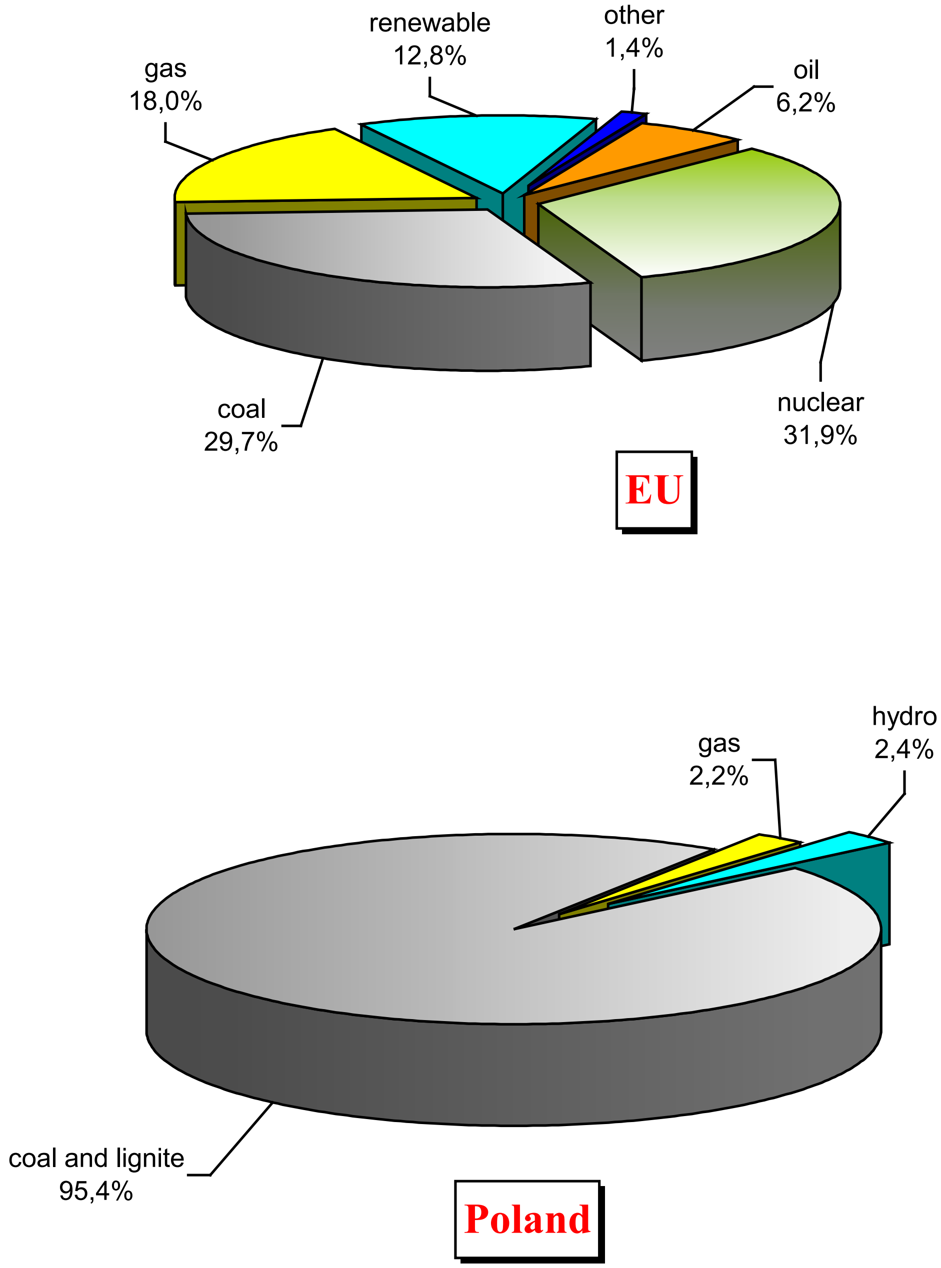
Fig. 4. Structure of final energy consumption in Poland



Source: IEA, OECD: Energy Balances of OECD Countries

Fig. 5. Electricity consumption per capita in Poland and in EU-15

Electricity consumption per capita is substantially lower in Poland than the EU average (Fig. 5). Recently the consumption almost does not change due to the effect of transformation. In EU the electricity consumption is growing and therefore the difference between per capita consumption in EU and in Poland is also growing. It should be expected that when the transformation reserves are exhausted, the demand for electricity will grow in Poland according to the economic growth rate, according to the structural adjustments towards the less energy intensive composition of economy and according to the pace of introduction of the energy saving technologies.



Source: Energy Market Agency

Fig. 6. Structure of inputs to electricity generation in Poland and in European Union 2004

The structure of fuel inputs to electricity generation is dominated in Poland by coal and lignite and is quite different from the structure in the European Union (Fig. 6). This creates not only serious environmental problems, connected with the emissions of sulphur dioxide, nitrogen oxides and carbon dioxide, but also the security of supply problems due to the lack of fuel diversification though the coals are of domestic origin.

2.3. Forecast of energy demand to 2030

The economic forecast prepared by the Gdańsk Institute for Market Economics [7] was applied in the study [6] for elaborating the forecast of energy demand. The economic forecast comprised the time horizon to 2025 and included some elements of development cycles. After the consultations with Polish experts and IAEA experts the cyclic elements were removed from the forecast, under the assumption that in the long term forecast the cyclic fluctuations will fit within the band of the expected scenarios of economic development.

The forecast of final energy demand, including the electricity demand, was elaborated for three scenarios of economic development: Base, Optimistic and Pessimistic. The Base scenario was constructed under the following assumptions [7]:

1) National political situation will slowly stabilise, which means natural 4-year political cycles with continuation of the economic policies despite the change of governments.
2) International situation will be stable, with Middle East conflicts gradually ending, which will stabilise the fuel prices. The economic performance of the most important economic partners of Poland will be relatively good.
3) The economic growth rate will be moderately high in Poland to 2030. The effects of EU membership, including the convergence policies and high absorption of EU funds, will positively stimulate the economic growth.
4) The inflow of foreign investment and the growth of exports to the EU markets will be moderately high.
5) Poland will join the ERM-II (Exchange Rate Mechanism) around the year 2008 and the Euro zone in 2010 - 2011.
6) Relative equilibrium of state budget will be achieved before 2008.
7) The trade balance will be in general negative (imports will exceed exports).
8) The unemployment will be gradually reduced and the employment rate of the population will increase.

The Optimistic scenario assumes that the economic growth will be accelerated due to, among others, removing the bureaucratic barriers for the entrepreneurs and simplifying the system of economic regulations. This would require the pro-reformatory parliamentary majority. It should be underlined that the Optimistic scenario is quite similar to the scenario assumed in „Energy Policy of Poland to the Year 2025". The Pessimistic scenario may become reality if the anti-reformatory or populist parties would assume the power and keep it for at least 8 years.

It has been assumed in the economic forecast that the basic trends observed from the beginning of market oriented transformation will be continued but at a degree lower than before: the share of services in GDP will be increasing, with the simultaneous reduction of industry and agriculture shares. In this way the structure of Polish economy will approximate to the structures of the highly developed economies. Structural shifts will also take place within the industry. The manufacturing industry will increase its share in value added of this economic sector. The other components of the industry, mainly coal mining, will generate relatively smaller part of GDP than currently.

Table 1. Forecast of annual average GDP growth

Scenario	2004-2010	2011-2015	2016-2020	2021-2025	2026-2030
Pessimistic	3.44	2.73	2.90	2.96	2.95
Base	4.15	4.56	5.11	5.14	4.93
Optimistic	4.79	5.85	6.48	6.31	5.85

Table 2. Forecast of GDP per capita (PLN'2002) [6]

Scenario	2010	2015	2020	2025	2030
Pessimistic	27,080	31,210	36,390	42,830	50,790
Base	28,420	35,780	46,390	60,630	79,070
Optimistic	29,660	39,700	54,910	75,840	103,320

The statistics of energy intensity and the projections of the macroeconomic scenarios were the inputs to the projections of useful energy demand (MAED model) and final energy demand (BALANCE model) – including the electricity demand. According to the results of model computations [6] it is expected that the demand for final electricity will increase to 2030 by 94% in Base scenario, by 152% in Optimistic scenario and only by 35% in Pessimistic scenario. As it could be expected, the electricity demand will increase most quickly in the services sector and in households (Table 3).

The coefficients of electricity consumption elasticity in relation to GDP[3] (Table 4) are in the Base scenario lower before the year 2010 than in the decade 2011-2020. This is the result of the still active effect of transformation. Its influence will be reduced in the further years. In the next decades the coefficient of elasticity will once more decrease, due to the expected introduction of new energy saving technologies – according to the EU energy policy. The indicators of GDP electricity intensity will decrease correspondingly.

Table 3. Final electricity demand [TWh] by economic sectors, Base scenario

Sector	2003	2010	2015	2020	2025	2030
Industry and construction	39.2	40.2	43.1	54.3	54.3	59.9
Transport	4.8	4.6	4.6	4.7	5.0	5.2
Agriculture	4.3	4.4	4.5	4.7	4.7	4.8
Services	28.1	33.8	39.4	47.8	58.3	71.4
Households	22.6	24.1	27.7	33.4	41.1	50.6
TOTAL	98.8	107.1	119.3	144.9	163.4	191.8

[3] Elasticity of electricity consumption in relation to GDP is the ratio of electricity consumption growth to GDP growth in a given year or in the other period of time.

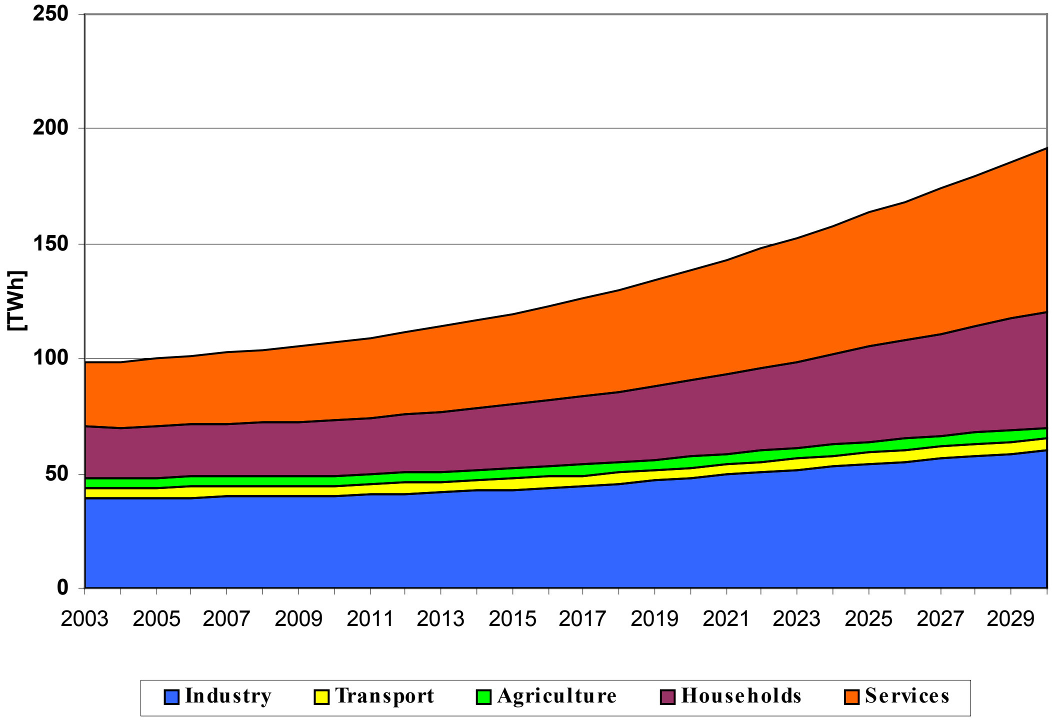


Fig. 7. Forecast of final electricity demand by economic sectors, Base scenario [6]

Table 4. Forecast of electricity consumption elasticity in relation to GDP, Base scenario[6]

Years	2004-2010	2011-2020	2021-2030	2004-2030
Coefficient of elasticity	0.277	0.635	0.565	0.525

3. Forecast of electricity generation structure

3.1. The substance of generation structure forecasting method

The methods and models recommended by the IAEA were applied in [6] to elaborate the forecast of the economically optimal structure of electricity generation sources. In particular the projections of renewable energy sources (RES) generation and cogeneration (CHP) were applied which result from the international obligations of Poland and from the analysis of the feasibility of fulfilling these obligations, taking into account the potentials of RES and CHP technologies. The electric system sources were optimised with the use of WASP IV model. This model allows to define the structure of sources with the minimum discounted costs of generation, taking into consideration the optimum margin of power in the electric system. In the first stage of calculations the cost optimal structure was defined. It was subsequently subjected to the analysis of sensitivity and was verified from the viewpoint of the possibility of financing the necessary investments. This verification brought the corrections to the optimising computations in order to obtain the structure of generation sources with the higher probability of implementation in the market conditions.

3.2. Basic assumptions to the forecast of new system sources structure

3.2.1. Forecast of fuel prices

The prices of fuels, and particularly of natural gas and coal, to the large extent decide on the economic competitiveness of the individual electricity generation technologies. The prices are also important for the optimisation of power demand coverage curve, taking into account the emissions of sulphur dioxide, nitrogen oxides and carbon dioxide. The forecast of fuel prices (Table 5) was constructed basing on the projections published by the leading international organisations active in the energy sector [8-11]. The forecast by the European Commission [9] was assumed as the reference scenario for the natural gas prices. The prices of imported coal were assumed according to the forecast by the International Energy Agency (IEA). Prices of nuclear fuel were based on EdF information. The influence of the eventual deviations of primary energy prices was subject to the research within the sensitivity analysis.

Table 5. Reference forecast of primary energy prices (USD'2000, prices of imports to the European Union)

	2003	2010	2020	2030
Crude oil (USD/bbl)	27.0	29.5	32.1	35.0
Natural gas (USD/1000 m^3)	94.9	106	148	198
Coal (USD/t)	38	40	42	44
Nuclear fuel (USD/kg)	1500	1550	1630	1720

Lignite is not present at fuel markets. In Poland the prices of primary energy unit in lignite are different depending on the basin: from the level of 40-42 USD'2000/toe in Bełchatów, through 48-53 USD'2000/toe in Konin area to about 60 USD'2000/toe in Turoszów. For the new prospective deposits in Legnica basin the costs of lignite production may be higher because of the necessity to cover the large investment expenditures and because of the higher proportion Overlayer/Coal layer. Simultaneously, the more efficient production technologies should be applied in the new basin. It is estimated, rather conservatively for the purpose of nuclear energy development, that the price of this lignite will be at the level of 60 USD'2000/toe.

3.2.2. Fuels availability

Coal. Recoverable reserves of coal in the existing mines in Poland will be sufficient for 38-40 years. The potential new mines, with considerably higher production costs, may extend this period to 100 years. This coal may however be not competitive in relation to imported coal, so the imports to the existing power plants are not excluded in the longer term perspective. World reserves of coal may be sufficient for about 200 years with the current production levels. For these reasons any limitations of coal availability were not assumed in the computations of optimal paths of electricity generation sources within the time horizon of the forecast.

Lignite. Recoverable reserves and production quantities will not decrease to 2020 in the existing lignite mines. After 2020, production from the operational deposits of Konin basin will be reduced but the new deposits Piaski and Uniejów will become operational. It is expected that the total annual production of lignite from the existing basins (including Piaski and Uniejów deposits) may reach 70 million tons. It has been assumed that Legnica basin, if developed, may supply the first quantity of 4.5 million tons in 2021, and gradually reach 40 million tons of production by 2030.

Natural gas. Existing indigenous resources of natural gas constitute the considerable supplement of imports from the security of supply viewpoint. Their importance for the power sector is however limited. In general it is feasible to use the locally produced gas only in the cogeneration sources. World reserves of natural gas are estimated at 67 years with the current level of production [12]. Therefore the limitations of gas availability are not expected within the time horizon of the forecast, assuming the diversification of supplies to Poland, in the form of pipeline transmission and also in the forms of Liquefied Natural Gas (LNG) and Compressed Natural Gas (CNG).

Renewable energy sources (RES). The sources of renewable electricity, available in Poland at the acceptable cost (which means the market price of electricity plus the statutory surcharge of 240 PLN'2004/MWh), amount to approx. 20.4 TWh[4]. This quantity is composed of:

- 8 TWh of hydro energy (doubling of the present level, with the necessity to construct new hydro plants at Vistula river),
- 2.1 TWh of the maximum available quantity of biomass of forest origin,
- 2.5 TWh from the energy crops,
- 7.8 TWh of wind energy.

It has been assumed that the wider application of the other technologies, including geothermal, fuel cells and photovoltaics, may be possible only after the time horizon of the forecast.

Imports of electricity. Polish power system is a part of UCTE system. Poland is therefore connected to the EU electricity market but the transborder connections are not sufficiently strong for imports to constitute the substantial component of national security of supply. For this reason, within the analysis aimed at the selection of the optimal technologies of electricity generation, the imports may not be considered the long term source of covering the national electricity demand.

3.2.3. Environment protection

It has been assumed in the optimising computations that the atmospheric emissions will be subject to the following limits resulting from the international protocols and obligations:

- Second Sulphur Protocol limiting the total national emissions of SO_2 (down to 1398 kt by 2010),
- Second Nitrogen Protocol limiting the total yearly national emissions of NO_x to 880 kt by 2010),

[4] Information from the Association of Renewable Energy, 2005

- Kyoto Protocol limiting the total yearly national emission of CO_2 to 435 Mt by 2010,
- EU Accession Treaty limiting the emissions of sulphur dioxide and nitrogen oxides from large combustion plants (454 kt SO_2 and 254 kt NO_x from 2008, 426 kt SO_2 and 251 kt NO_x from 2010, 358 kt SO_2 and 239 kt NO_x from 2012); this regulation in the Accession Treaty is however incompatible with the other regulation which provides for the individual derogations for the listed combustion sources; the incompatibility between the individual derogations and total limits disables to apply in practice the individual derogations,
- National Allocation Plan for CO_2 emission allowances of December 2005, based on the limit granted by the European Commission for the years 2005-2007 for the sources participating in the emission trading scheme. For the system sources of electricity the annual limit of 125 Mt of CO_2 was assumed to the year 2014. Reduction of this limit to 120 Mt for the years 2015-2019 and to 110 Mt since 2020 is expected, in line with the plans of the European Commission. For the emissions which exceed the above limits the payments are assumed according to the forecast of market prices of emission allowances in the European system of trading. These payments constitute the component of the variable costs of electricity generation.

3.2.4. Determined capacities of the existing system sources

Determined net capacities of system power plants and CHP plants and net load of the system (Fig. 8), after deduction of the net generation by autoproducers and dispersed capacities, were defined basing on the plans of modernisations, liquidations and replacements of the existing equipment.

The total net capacity of the determined system sources will decrease from 27.6 GW in 2003 to 21.3 GW in 2030 due to technological wear out of the equipment.

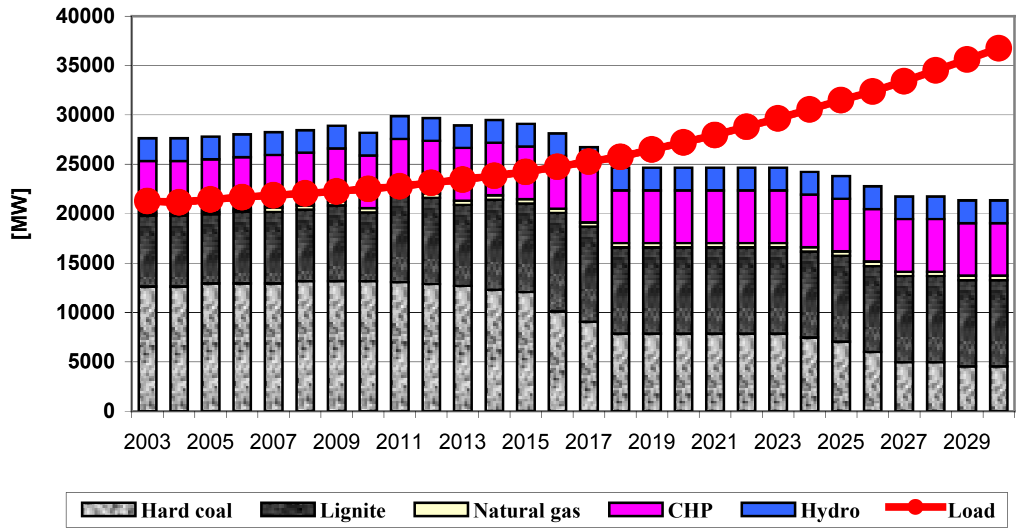


Fig. 8. Projection of the system load and planned net capacities of existing system sources, Base scenario

3.2.5. Technical and economic characteristics of new generation units

The parameters of the new capacities considered within the process of system sources optimisation have been assumed according to the leading international sources [13,14,15]. Data published by World Nuclear Association [13], Nuclear Energy Agency [14] and the experts of the European Parliament [15] were accepted as the referential (Table 6). Variable costs of generation do not include costs of fuel, which constitute the separate category in the model computations.

The following technologies were selected to the analyses:

<u>lignite fired:</u>

- 500 MW unit with supercritical parameters and the installation of wet desulphurisation (PC),
- 150 MW unit with atmospheric fluidised bed boiler (AFBC),

<u>coal fired:</u>

- 400 MW unit with the installation of wet desulphurisation (PC),
- 300 MW unit combined cycle unit with coal gasification (IGCC),
- 150 MW unit with pressurised fluidised bed boiler (PFBC),

<u>natural gas fired:</u>

- 300 MW combined cycle gas-steam unit (CCGT),

<u>nuclear technology:</u>

- 1500 MW unit.

The above list does not mean that precisely the sources with the mentioned parameters and capacities will be constructed. The actual solutions will depend on the offers of equipment suppliers, on the possibilities of operation at the actual sites etc. This issue has however no substantial meaning for the long term forecasts.

Table 6. Technical and economic characteristics of new electricity generation units

Fuel	Lignite		Coal			Natural gas	Nuclear fuel
Type of unit	PC	AFBC	PC	IGCC	PFBC	CCGT	
Net capacity (MW_e)	500	150	400	300	150	300	1500
Investment expenditures ($'00/kW)*)	1280	1100	1160	1450	1240	590	2170
Years of construction	4	4	4	4	4	2	8
Fixed O&M costs ($'00/kW-year)	30.0	30.0	25.0	52.0	35.0	13.5	55.0
Variable O&M costs ($'00/MWh)	2.0	2.0	1.82	1.62	1.92	0.5	0.4
Net efficiency	0.415	0.415	0.43	0.45	0.43	0.58	0.36
Unavailability factor (%)	5.0	5.0	3.0	10.0	9.0	4.0	4.0
Maintainance time (days/year)	42	42	40	42	42	20	30

*) includes the cost of capital freezing during construction time and the obligatory deduction for nuclear plants liquidation fund

Sources: NEA, IEA: Projected Costs of Generating Electricity, 2005 Update, Implementing Clean Coal Technologies

The list of potential generation sources does not include coal fired plants with CO_2 sequestration, because this technology is not yet demonstrated to the level which would allow to estimate the necessary investment expenditures and operation costs.

3.3. Results of optimising computations

3.3.1. Screening curves

The characteristics of the potential generation units enable to construct so-called screening curves (curves of economic load of generation units), which constitute the first approximation for the results of optimising computations. The curves show for the given year the ranking of the electricity generation costs by the units of various technologies as a function of the units capacity utilisation factor during the year.

For the year 2021, which for the logistics reasons may be the first year of nuclear units operation, and for the reference conditions of system sources operation, i.e.: reference forecast of primary energy prices (Tab. 5), real discount rate of 5% and the CO_2 emission allowance cost of 10 USD'2000/tCO_2, the nuclear sources are competitive against all fossil fuel sources at the capacity utilisation factor exceeding 65% (Fig. 9), i.e. at capacity utilisation time exceeding 5670 h/year. Towards the year 2030 the competitive advantage of the nuclear technology increases (Fig. 10).

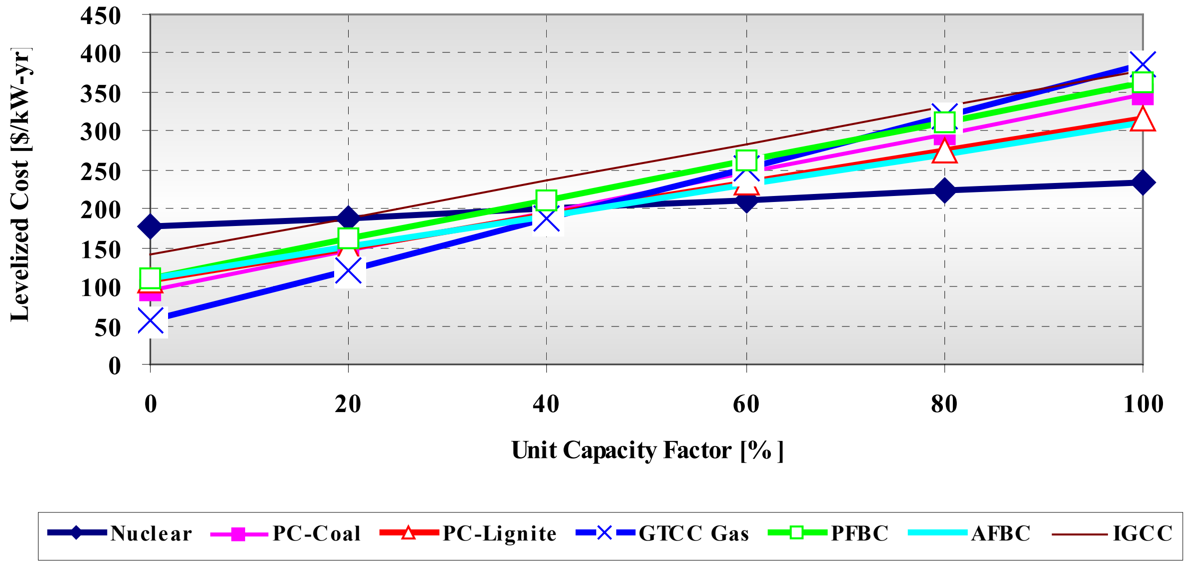


Fig. 9. Screening curves for fuel prices of the year 2021, with 5% discount rate and the CO_2 emission allowance cost of 10 USD/t

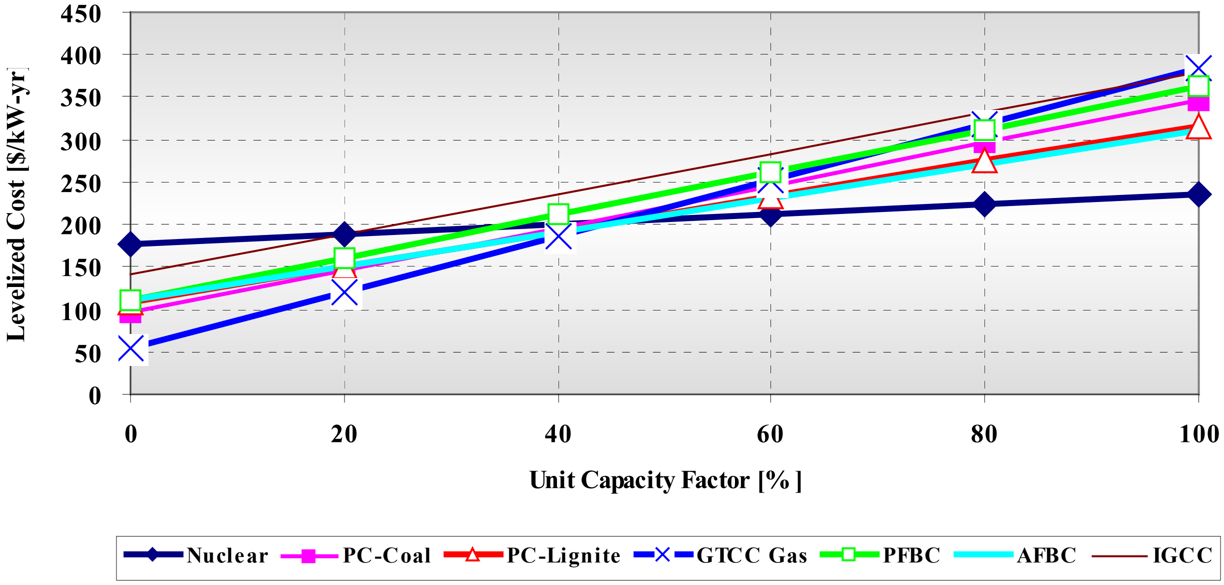


Fig. 10. Screening curves for fuel prices of the year 2030, with 5% discount rate and the CO_2 emission allowance cost of 10 USD/t

At the discount rate of 10%, which reflects the market conditions of the expensive capital, the competitive advantage of nuclear sources is lower due to the high share of capital cost in the structure of nuclear generation costs. Despite this, with the CO_2 emission allowance cost at the level of 10 USD/tCO_2, the nuclear units are competitive since the year 2024 as the base load units, at the capacity utilisation time exceeding 80%.

At 5% discount rate the nuclear units covering the base load of electricity will be competitive since 2024 even if the price of CO_2 emission allowance will decrease to zero.

3.3.2. Cost optimal structure of generation sources

The optimising computations were conducted with the use of WASP IV model for the following reference conditions:

- Base scenario of the economic development of the country,
- reference forecast of fuel prices,
- real discount rate of 5%/year,
- existing and expected limits of annual CO_2 emissions (125 Mt to 2014, 120 Mt in 2015-2019 and 110 Mt since 2020),
- price of CO_2 emission allowance at the level of 10 USD/tCO_2,
- developed lignite basin Legnica, with the price of this coal at the level of 60 USD’2000/toe.

As a result of computations, the cost optimal structure of new generation sources has been obtained (Fig. 11). The operation of the first nuclear unit starts in this structure in 2021, following the assumed period of time necessary for the preparation of investment and the cycle of nuclear plant construction.

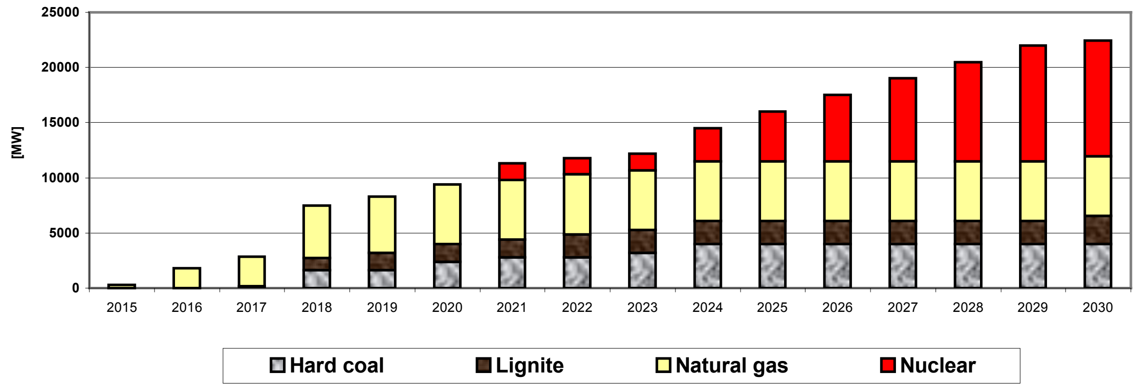


Fig. 11. Cost optimal structure of new generating units for the reference conditions of development

Besides the nuclear units, the new 400 MW PC-type coal fired units appear in the cost optimal structure. Concerning lignite, seven new 150 MW units of fluidised (AFBC) type and three 500 MW units of pulverised coal type will start operation by 2030. New gas fired sources do not appear in the optimal structure of system sources since 2021. They will not be competitive in relation to nuclear and coal fired sources at that time.

3.3.3. Conclusions from the analysis of sensitivity of optimisation results against the changes in assumptions

The analysis of sensitivity of optimisation results against the changes in assumptions has proved that the most important parameters which influence the cost optimal structure of the system sources are the following:

- growth of GDP and the resulting growth of electricity demand,
- cost of CO_2 emission allowances,
- discount rate.

For the Optimistic scenario of economic development and the accordingly growing electricity demand, the capacity of nuclear plants increases to 13 500 MW in 2030 in the cost optimal structure. For Pessimistic scenario the corresponding structure contains only one nuclear unit with the net capacity of 1500 MW. Increase in emission ceilings may cause only some postponement of the nuclear investment but not their cancellation. Also the more expensive capital may be the reason for the similar postponement within the optimal structure. The other parameters, namely: gas prices escalation and lignite prices, do not influence in practice the optimal path of nuclear power development, if the changes in their values do not diverge too far from the reference conditions.

3.3.4. Investment expenditures

The cost optimal structure of new generation sources is characterised by a very high level of necessary investment expenditures (Fig. 12): up to as much as 12 to 14 billion PLN’2000 per annum in the years 2015-2024. The main reason for so high expenditures is the large capital intensity of nuclear power investments. The experts assess that ensuring the financing for such investments would be very difficult if the state budget subsidies are excluded or substantially limited, which is the precondition for the appropriate operation of the competitive market of electricity. The annual expenditures for generation capacities during the period 2015-2024 would be twice as high as they were in the years 1994-1997 when the investments were financed through the long term power purchase contracts.

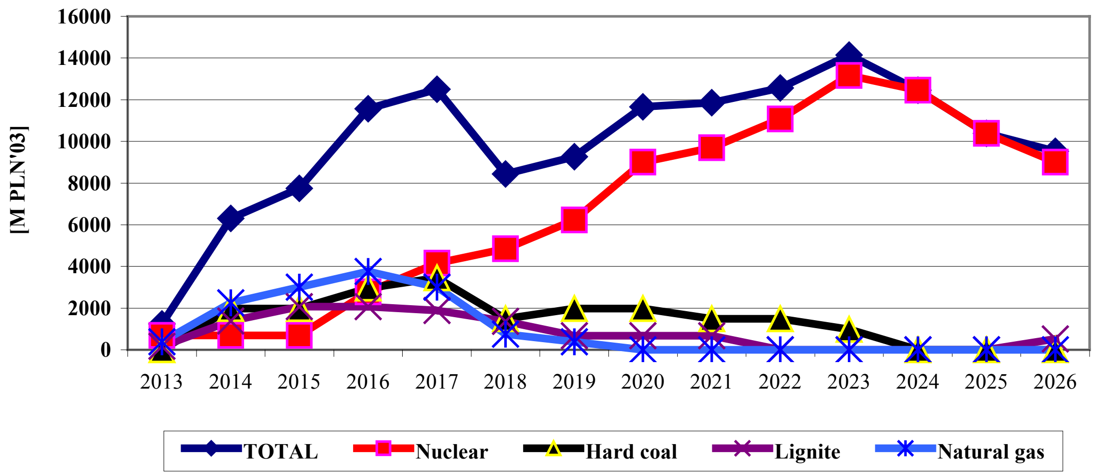


Fig. 12. Investment expenditures for new generating capacities in the cost optimal structure of generation and the reference conditions of development

3.3.5. Optimal structure of sources for the limited pace of nuclear power construction

Difficulties in covering the high cumulated investment requirements, particularly the nuclear investment requirements, may result in limiting the pace of nuclear plants construction. Because the expenditures for the nuclear infrastructure should be spread out in time, it was assessed that the acceptable pace of construction should not be slower than 3 units, each of 1500 MW net capacity, put into operation before the year 2030. The actual number of nuclear units constructed by 2030 will depend on numerous factors which are now difficult to assess. With only 3 nuclear units ready to 2030, the structure of new electricity sources will change in comparison with the cost optimal structure. The lacking nuclear capacities from the cost optimal variant may be substituted in this case by lignite or coal fired units. Any new gas fired units are not cost competitive because of the high prices of gas.

The lignite option should take into account the necessary expenditures for the development of Legnica basin. The currently exploited lignite deposits are not sufficient to cover the demand in the time horizon of the forecast. The expenditures for Legnica basin development are roughly estimated at 25 billion PLN’2005. The amount of these expenditures should be defined more precisely in the separate study.

The variant with the nuclear capacity limited to 3 units of 1500 MW each by 2030 and without the development of Legnica basin (Fig. 13) must include coal fired units as the main new capacities. New lignite fired units will be very limited in such variant because they will have to base on the existing deposits of lignite. In such case, modern coal fired capacities will have to be constructed in addition to the nuclear units. Such structure is characterised by considerably lower total investment expenditures (Fig. 14). In this structure the domination of coal in electricity generation will be continued (Fig. 15) but it will later decrease due to the construction of further nuclear plants after 2030.

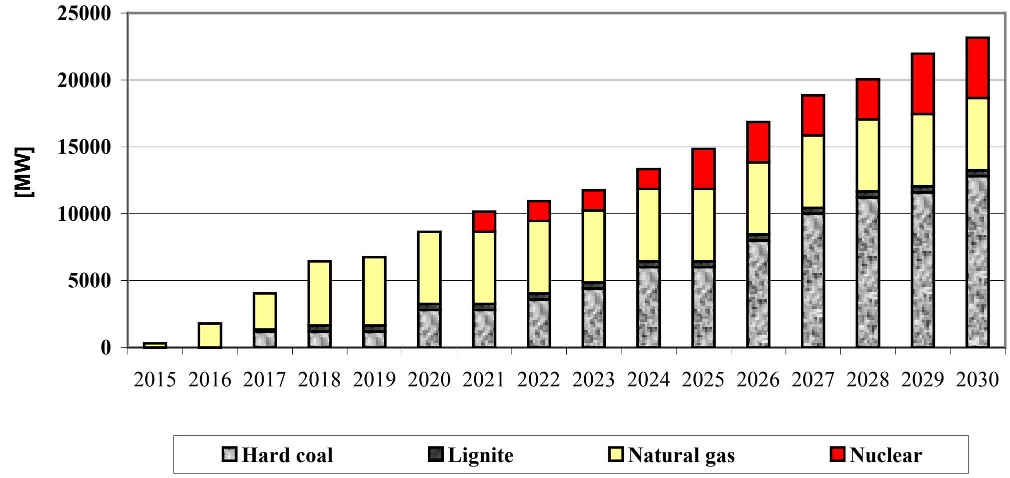


Fig. 13. Optimal structure of new generating units for the variant with the limited nuclear construction (3 units by 2030) and without development of Legnica lignite basin

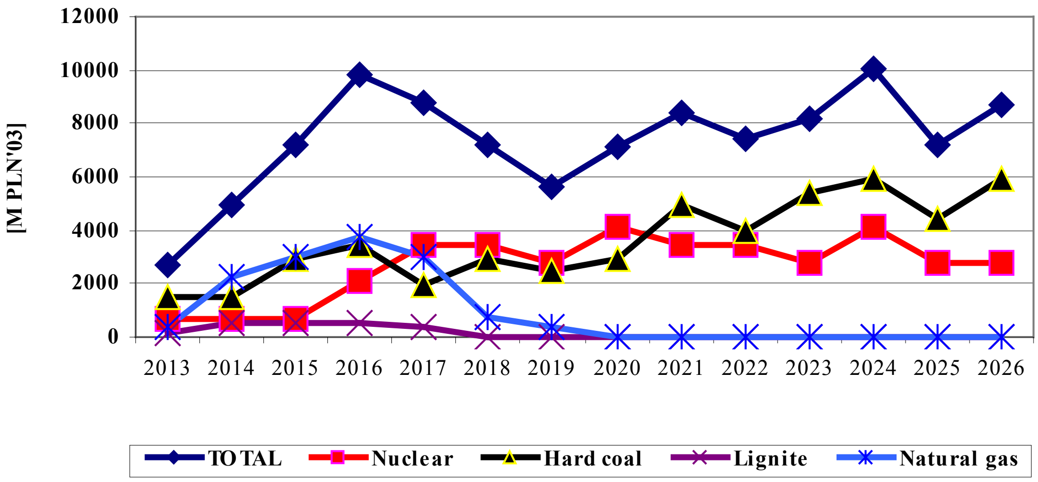


Fig. 14. Investment expenditures for new generating capacities in the structure with limited nuclear construction and without development of Legnica lignite basin

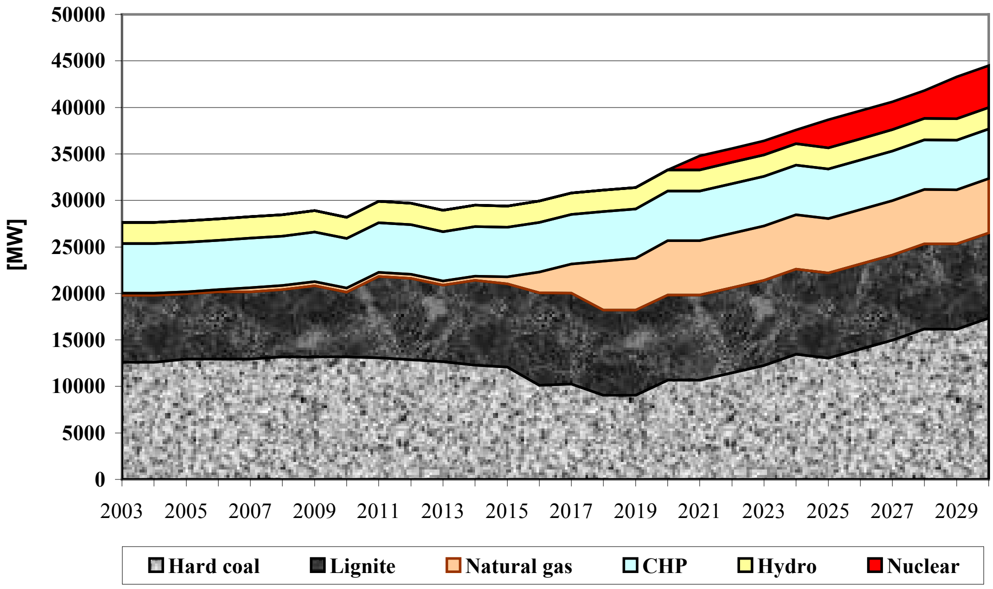


Fig. 15. Forecast of fuel structure of generating capacities, variant with limited nuclear construction and without development of Legnica lignite basin

4. Comparison of fossil fuelled power plants and nuclear plants from the viewpoint of environment protection

4.1. Health hazards resulting from fossil fuels combustion [1], [17]

Thermal power plants, in which organic fuels are burnt, cause the substantial health hazards due to atmospheric emissions of the harmful pollutants. Emissions from coal fired plants are the most hazardous. The flue gases from such plants contain the following dangerous components: sulphur dioxide (SO_2), nitrogen oxides (NO_x), particulates as well as harmful heavy metals and radioactive elements which originate from steam coal.

The sulphur dioxide is the cause of bronchi and lungs irritation as well as disorders of cardiovascular system if present in the air at higher concentrations. The long term exposure to sulphur dioxide is the reason for the substantial growth of illnesses and fatalities, particularly during the periods of smog, i.e. the dense fog mixed with the smoke and flue gases. Visible growth of fatalities was observed in large cities and industrial agglomerations when the smog appeared at the particularly disadvantageous weather conditions (lack of wind, thermal inversion) which disabled the dispersion of emitted pollutants.

Currently used installations for SO_2 and NO_x mitigation in coal fired plants are very expensive, particularly in investment expenditures. They also consume quite large operational amounts of electricity.

Particulates are captured by electrostatic filters. Their efficiency may achieve in theory even 99.8% but is lower in practice. The small particles of the diameter below 2.5 µm ($PM_{2.5}$) are particularly dangerous. They easily permeate through the filters and they penetrate deeply to the human lungs, causing the illnesses of the respiratory system, chronic bronchitis and probably also the lung cancer.

During the last dozen of years, intensive activities, aimed at the reduction of the environmental impacts of electricity generation, were conducted in the Polish power sector. The emissions in 2004 were compared with 1990 levels in [17]. According to this publication, SO_2 emissions were reduced in 2004 to 44% of 1990 level, NO_x emissions – to 61% and particulate matter emissions – to 8%. Despite these achievements the emissions of gaseous pollutants from thermal power plants are in Poland still much higher than in Western Europe. In relation to 1 kWh of generated electricity, the emissions of SO_2 are in Poland 2 times higher and the emissions of NO_x – 1.3 times higher than the average of EU-15 countries.

Reducing the emissions to the current levels of EU-15 would be possible through the further diversification of electricity generating sources, and particularly through:

- wider application of natural gas instead of coal in thermal power plants and particularly in CHP plants; this option is however very expensive because of high prices of gas,
- higher share of electricity from renewable sources (RES) within the economically feasible potential of these sources,
- introduction of nuclear plants which do not emit any pollutants similar to sulphur dioxide, nitrogen oxides and particulates.

4.2. Threats resulting from nuclear power use [1], [16]

Nuclear power plants influence the environment mainly through the discharges of radioactive substances. The quantities of discharge depend on many factors, and among others: reactor capacity, number of leaking fuel rods and the degree of removal of the nuclear fission products from the discharged gases and liquids. Many years of experience indicate however that it is not difficult to keep the discharged quantities substantially below the allowed levels.

International Commission on Radiological Protection (ICRP) defined the size of the recommended level allowed for people at 1 mSv/year (one milisievert per year). This size is accepted as the standard in EU countries. In some countries however the national radiological protection bodies introduce the additional limits which are aimed at ensuring the margins of safety in case of simultaneous radiation from several nuclear power plants.

In Germany the limit of the radioactive dose from nuclear power plants has been set at the level of 0.3 mSv/year. In Finland this figure is 0.1 mSv/year. In France the formal standard is 1 mSv/year but the discharge limits correspond to the substantially lower doses. According to [16], the maximum doses corresponding to discharge limits would amount in France to 0.3 mSv/year while the actual doses outside one of the plants were at the level of 0.01 mSv/year, 30 times less than discharge limit levels, and the annual average dose for France population is 0.001 mSv, i.e. 1 μSv/year (one microsievert per year).

It should be reminded for comparison that the average background of natural radiation at the Earth is 2.4 mSv/year, but for example the natural background in Finland is three times higher and amounts to approx. 7 mSv/year. The additional dose of 0.001 mSv/year caused by power plants is therefore in practice not noticeable at the background of natural radioactivity.

4.3. External costs of electricity generation [17]

When comparing the electricity generation costs in various technologies, the notion of so-called external costs is being introduced [17] in addition to the generation costs covered by plants. The external costs comprise health costs, costs of environmental damage, including the costs induced by the greenhouse effect, and the costs of possible failures. The health costs have the highest share in the structure of external costs while the costs incurred by the greenhouse effect are still the subject of discussion.

In the recent years, the European Commission evaluated the external costs of electricity generation within the research programme called *ExternE*. The original methodology of tracking the ways in which pollution influences the society and of calculating the connected costs has been elaborated in the framework of *ExternE* programme [17]. Comparison of various health consequences of atmospheric pollution and their financial evaluation proved that the increase in mortality rate due to the chronic exposure constituted the highest item in the total health costs.

The methodology applied by *ExternE* consists in the evaluation of the number of years of life lost (*YOLL – years of life lost)* due to health hazards, caused by the adverse impacts of atmospheric pollution. For the EU countries the financial equivalent of shortening the expected life length of one person by one year amounts to 52 000 Euro (applying the discount rate of 3%).

External costs of electricity generation in Poland were defined in the study [17]. Only the health costs incurred by the emissions of atmospheric pollutants (SO_2, NO_x and PM_{10}) and the costs of climate warming due to the CO_2 emission were taken into account. The external costs per 1 kWh of electricity generated by Polish public power plants and CHP plants in 2004 are presented in Table 7.

Table 7. External costs of electricity generation in public power plants and CHP plants in Poland in 2004 [mEuro/kWh] [17]

Air pollutant	Public power plants		Public CHP plants	Average for all plants in Poland
	Coal fired	Lignite fired		
SO_2	18.3	27.5	13.6	20.5
NO_x	3.8	3.2	2.4	3.3
PM_{10}	3.5	1.6	3.9	3.1
Total	25.6	32.3	19.9	26.9
CO_2	19.2	23.5	13.9	19.6
Grand total	44.8	55.8	33.8	46.5

Table 8 presents the total aggregated external costs of electricity and heat generation in Polish power plants and CHP plants in 2004. They amount in total to approx. 7 billion Euro, of which 1 billion Euro are the external costs of heat production. This figure was equal to 1.7% of Poland's GDP in 2004.

Table 8. Total external costs of electricity and heat generation in Poland in 2004 [17]

Air pollutant	Annual external costs	
	billion Euro	%
SO_2	3.11	44.0
NO_x	0.50	7.1
PM_{10}	0.47	6.7
Total	4.08	57.8
CO_2	2.98	42.2
Grand total	7.06	100.0

The external costs connected with electricity generation in nuclear plants were also evaluated within the framework of *ExternE* programme. These costs included the full cycle of nuclear fuel, also the reprocessing of spent fuel. In United Kingdom the external costs of nuclear generation amount to 0.46 mEuro/kWh [17]. Similar figures were obtained for France, Germany and Sweden. For Poland they would probably be even lower.

The comparison of external costs for Poland indicates that even when neglecting the costs of rivers pollution by sewage waters from coal fired plants and neglecting the costs of saline waters discharge from coal mines to the rivers, the external costs caused by the emissions of pollutants and CO_2 to the atmosphere amount to 46 mEuro/kWh while for the nuclear fuel cycle they would be lower by two orders of magnitude.

It therefore turns out that after taking into account the external costs the nuclear power plants are the substantially cheaper sources of electricity for the society than the fossil fuel power plants (burning coal, lignite or natural gas). This conclusion applies to the whole European Union, including Poland. It is the additional argument in support of the nuclear power development in Poland.

5. Summary and conclusions

1. There is a necessity to build nuclear power plants in Poland, in order to ensure the country's energy security and to cover the expected demand for electricity. Construction of nuclear plants will be rational from all the following viewpoints:
    - energy aspect which means application of the available resources and the necessity to increase the diversification of primary energy sources,
    - economic aspect which means the criterion of the minimum discounted costs of electricity generation,
    - environmental aspect which means compliance with the current and expected environmental requirements of the European Union, taking into account the issue of external costs which is very disadvantageous for the fossil fuels generation.
2. The expected conditions influencing the development of the energy sector, i.e. the Base or Optimistic scenarios of the economic development, expected fuel prices, the assessment of investment expenditures for various electricity generation sources,

expected CO_2 emission costs and real discount rate at the level of 5%, justify the beginning of first nuclear plant operation by the year 2021.

3. High investment expenditures for the construction of nuclear power plants will limit the possible pace of building the subsequent nuclear units. In these conditions the necessity to build new modern coal fired plants will also occur.
4. High investment expenditures, which would be necessary for the development of Legnica lignite basin, will be the important factor influencing the optimal structure of new electric capacities. If Legnica basin is not put into operation, then the nuclear capacities postponed because of the investment limitations will have to be replaced by coal fired plants.
5. Development of nuclear power in Poland, initiated by the beginning of first plant operation in 2021, will substantially reduce the health hazards for the society which are the consequence of organic fuels burning and emissions of harmful air pollutants.

6. References

1. Z. Celiński: *Nuclear Energy and the Society* (in Polish). Wydawnictwo Naukowe PWN, Warsaw 1992.
2. J. Marecki: *Role of Nuclear Energy in Covering the Energy Demand in Poland up to 2010*. Archiwum Energetyki 1992, No. 1.
3. J. Marecki, T. Wójcik: *Strategic and Economic Issues of the Nuclear Power Development* (in Polish). Spektrum 1997, No. 5.
4. J. Marecki: *Prospects of Electric Power Development in Poland to 2020* (in Polish). Przegląd Elektrotechniczny 2002, No. 7.
5. J. Marecki: *Polish Energy Sector Yesterday, Today and Tomorrow* (in Polish). Archiwum Energetyki 2004, No. 1/2.
6. *Definition of the Optimal Scope and Pace of Nuclear Power Development in Poland* (in Polish). Energy Market Agency, 2006.
7. *Long Term Macroeconomic and Sectoral Forecast of Polish Economy Development 2004-2025* (in Polish). Gdańsk Institute for Market Economics, 2004.
8. *European Energy and Transport Trends to 2030.* European Commission, 2003.
9. *World Energy, Technology and Climate Policy Outlook to 2030 – WETO.* European Commission, 2003.
10. *International Energy Outlook 2005.* US Department of Energy, Energy Information Administration (EIA).
11. *World Energy Outlook 2004.* International Energy Agency (IEA).
12. *BP Statistical Review of World Energy*, June 2004.
13. *The Economics of Nuclear Power*. World Nuclear Association, May 2005.
14. *Projected Costs of Generating Electricity*. Nuclear Energy Agency (NEA), 2005 Update.
15. *Implementing Clean Coal Technologies – Need for Sustained Power Plant Equipment Supply for a Secure Energy Supply*. Working Paper, STOA 117 EN, European Parliament, Dec. 2003.

16. A. Strupczewski: *Doses at the Normal Operation of Nuclear Power Plants* (in Polish). Biuletyn Miesięczny PSE, No. 8, 2005.
17. A. Strupczewski, U. Radović: *External Costs of Electricity Generation in Poland* (in Polish). Biuletyn Miesięczny PSE, No. 1, 2006.