

The reduction of atmospheric emissions after the implementation of first Polish nuclear power plant

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Abstract. In this work the environmental benefits in the atmospheric emissions after the implementation of 3,000 MW nuclear power plants were assessed and presented. To determine the quantity of avoided emissions of CO₂, NO_x, SO₂ and Hg compounds, harmonised stoichiometric combustion model dedicated to solid fuel fired power plant was created. To increase the credibility of the studies, future strict emission standards (Directive 2010/75/EU, BAT documents for LCP) were included as well. In conducted studies, representative samples of 3 different Polish solid fuels were examined (by comprehensive proximate and ultimate analysis) and used in assessment. It was proven that by the replacement of thermal solid fuel power plant by nuclear unit (with annual production rate of 22.4 TWh net) up to 16.4 million tonnes of lignite, 8.9 million tonnes of hard coal or 13.1 million tonnes of solid biomass can be saved. Further, for the case of lignite, the emission, at least, of 21.29 million tonnes of CO₂ (6.9% of all Polish emission in 2015), 1,610 tonnes of dust (0.4%), 16,102 tonnes of NO_x (2.2%), 16,102 tonnes of SO₂ (2.0%) and 564 kg of mercury (5.9%) can be avoided. For selected hard coal, calculated emission savings were equal to 17.60 million tonnes of CO₂ (5.7%), 1,357 tonnes of dust (0.4%), 13,566 tonnes of NO_x (1.9%), 13,566 tonnes of SO₂ (1.7%), 271 kg of mercury (2.9%), and for biomass - equal to 20.04 million tonnes of CO₂ (6.5%), 1,471 tonnes of dust (0.4%), 14,712 tonnes of NO_x (2.0%), 14,712 tonnes of SO₂ (1.8%) and 294 kg of mercury (3.1%).

1 Introduction

Polish power sector is currently undergoing a period of fundamental economic and technological reorganisation. In order to execute upcoming international pro-environmental programmes (i.e. Minamata Convention on Mercury, new EU energy policy, European CO₂ Emission Allowances Trading System), several low-emission power units and energy storage facilities need to be connected to the Polish electrical grid within the following 10-20 years. By the replacement of coal-fired (mainly lignite) units with renewable energy sources (RES) and nuclear power plants, it will be possible to reduce the quantity of

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national emissions of several pollutants substantially. Moreover, reorganised fuel structure of power sector will allow Polish authorities to adjust national emission rates (i.e. regarding CO₂ releases per every MWh of electricity) to the values proposed in new energy policy of European Union (i.e. within the EU Winter Package) [1]. What is particularly interesting in Poland, while RES have been already integrated in power grid (22.7 TWh generated in 2015 – approx. 45% from wind turbines and 50% from solid biomass boilers), nuclear power plants have not been operated in Poland yet.

To support national generation emission factors (i.e. concerning CO₂ or Hg), first Polish nuclear power plant (NPP) is going to be built in Poland in the next 12-15 years. It is planned to operate a 2-3 reactors with total capacity of 3,000 MW and to generate 22.4 TWh of electricity (approx. 14% of total generation in Poland in 2015) by 2030-2035 as well as up to 43.2 TWh from 6,000 MW of nuclear units by 2050. While first Polish NPP will be probably placed in Pomerania Voivodeship, second one will be located in eastern Poland [1,2]. Bidding process for selection of NPP technology for first power unit should start in 2018 – from the operational point of view, several generation III or III+ water cooled technologies will be taken into account, both PWR and BWR class).

As mentioned before, one of the main goals of the replacement of coal-fired power plants by NPP and RES in the reduction of atmospheric emissions. Nowadays, due to the vast consumption of hard coals (50.1% of total electricity in Poland was generated in coal-fired units in 2015) and lignite (31.5% of 165 TWh provided to the grid), power sector in Poland has become the largest emitter of CO₂ (51.5% of 310.3 million tonnes released from Poland in 2015), SO₂ (53.5% of 690.3 thous. tonnes), NO_x (28.8% of 713.8 thous. tonnes) and Hg (49.6% of 10.6 tonnes). Interestingly, only 8.8% of total quantity 317.7 thous. tonnes of dusts were introduced into the atmosphere from professional power sector [3].

In conclusion, when introduced, first Polish NPP should lead to the notably decrease of CO₂, SO₂, NO_x and Hg emissions first and seems to be a crucial part of future low-emission power market in Poland. By the replacement of coal-fired units with NPP, national consumption of hard coal and lignite in power sector may be lowered as well. To evaluate the possible both fuel and emission savings, calculation method dedicated to solid fuel combustion units was prepared.

2 Materials and methods

To assess the environmental benefits of the implementation of 3,000 MW net NPP (with total annual production of electricity equal to 22.3 TWh net), calculation tool based on stoichiometric method was adopted [4]. Air-fuel equivalence ratio was set at 1.2, average net efficiency of solid fuel power plants at 40% and annual capacity ratio at 85% (7,446 hr/yr). To simplify the calculations, the value of carbon content in slag was fixed at 3%, while in fly ash – at 4% (relatively high, i.e. to enhance the uptake of mercury on fly ash). Then, equation (1) was used to identify the quantity of CO₂, H₂O, O₂, N₂, SO₂, HCl and Hg in raw flue gas. To calculate the mass concentration at standard temperature and pressure (S_{STP}), Avogadro's hypothesis was included. Finally, all values at STP were corrected for the water vapour content of the waste gases and at a standardised O₂ content of 6% (S_{st} – reference conditions) [5].

$$\begin{aligned}
 & 8.33 \cdot 10^{-2} a C + 0.5 b H_2 + 3.57 \cdot 10^{-2} c N_2 + 3.13 \cdot 10^{-2} d S + 3.13 \cdot 10^{-2} e O_2 + \\
 & + 5.56 \cdot 10^{-2} f H_2O + 4.98 \cdot 10^{-3} g Hg + 3.13 \cdot 10^{-2} h Cl + \lambda M_s (O_2 + 3.76 N_2) = \quad (1) \\
 & = n_1 CO_2 + n_2 H_2O + n_3 O_2 + n_4 N_2 + n_5 SO_2 + n_6 HCl + n_7 Hg + n_8 C(a) + n_9 C(s),
 \end{aligned}$$

where: $a-h$ – different constituents contents (weigh fraction) in fuel (a – carbon, b – hydrogen, c – nitrogen, d – sulphur, e – oxygen, f – moisture, g – mercury, h – chlorine; see Table 1. and Table 2.), λ - air–fuel equivalence ratio, M_s – number of moles of oxygen delivered per 1 mole of fuel in stoichiometric conditions, n_i – calculated number of moles of selected component accumulated in flue gases from combustion process of 1 g of fuel (1 – carbon dioxide, 2 - water vapour, 3 – oxygen, 4 – nitrogen, 5 – sulphur dioxide, 6 - hydrogen chloride, 7 – elemental mercury, 8 – carbon in fly ash, 9 – carbon in slag).

Table 1. Ultimate analysis of selected fuels (air-dried samples) [4,6].

Fuel	C	H	N	S	O	Hg	Cl
	wt%					ppb	%
hard coal	60.05	4.07	1.36	0.46	7.83	76	0.13
lignite	55.19	4.49	0.65	1.76	17.32	545	0.07
solid biomass	50.32	5.64	1.52	0.08	31.95	38	0.30

Legend: C – carbon content, H – hydrogen content, N – nitrogen content, S – total sulphur content, O – oxygen content, Hg – mercury content, Cl – chlorine content

Table 2. Proximate analysis and calorific values of selected fuels (air-dried samples) [4,6].

Fuel	W	W _{ex}	A	V	FC	HHV	LHV
	wt%					MJ/kg	
hard coal	1.05	10.07	25.05	28.41	45.49	23.43	22.52
lignite	4.39	35.08	16.13	44.44	35.03	19.99	18.90
solid biomass	1.50	16.51	8.69	68.88	20.93	18.86	17.59

Legend: W – moisture content, W_{ex} – external moisture content, A – ash content, V - volatile matter content, FC – fixed carbon content, Q - higher heating value, LHV - lower heating value

To calculate the dust concentration in raw flue gases (at STP), empirical equation (2) were implemented.

$$S_{dust} = (10 A^r L_{dry} a_u + C_{fa} L_{dry}^{-1} B^{-1}) (21 - O_2^{st}) (21 - O_2)^{-1}, \quad (2)$$

where: S_{dust} - fly ash concentration in g/m^3_{st} , A^r – ash content in received fuel in %, L_{dry} – the quantity of dry flue gases per 1 kg of fuel, a_u – the ratio of the quantity of mineral matter accumulated in fly ash to total mineral matter in received fuel (fixed at 0.9 - for pulverised fuel fired boilers), C_{fa} – the stream of carbon in fly ash in kg/s, B – fuel consumption in kg/s, O_2^{st} – standardised oxygen concentration in flue gas (6% for solid fuels), O_2 – calculated oxygen concentration in raw flue gases. To determine the quantity of wet flue gas created per every 1 g of solid fuel, $n_1 \dots n_7$ shall be summed up.

Finally, to determine the annual emissions E_i of selected pollutants (restricted by the emission standards – Table 3), equation (3) was used.

$$E_i = 22.42 n_i B \rho_{iSTP} (1 - \eta_i) = 8.07 \cdot 10^{10} n_i P \eta_{el}^{-1} LHV_r^{-1} \rho_{iSTP} S_{ies} S_{ist}^{-1}, \quad (3)$$

where: B – annual fuel consumption in kg, ρ_{iSTP} – density of gaseous form of component at STP in kg/m^3 , η_i – capture efficiency of selected pollutant, P – annual net electricity generation in TWh, η_{el} – total net efficiency of power plant, LHV_r – lower heating value of fuel (in received state), S_{ies} – emission standard for selected pollutant in $\mu g/m^3_{st}$, S_{ist} – pollutant concentration in raw flue gases in $\mu g/m^3_{st}$.

To identify the impact of NPP on emission and fuel savings, 3 different types of solid energy carriers were analysed and used within calculations. They represent 3 solid fuels from Poland: hard coal, lignite and straw pellet. The results of ultimate and proximate

analysis dedicated to selected fuels were presented in Table 1. and Table 2. All lab test were performed using PN/EN ISO standards i.e. to determine the contents of 7 different elements (using atomic absorption spectroscopy and ion chromatography – LECO CHNS TruSpec, AMA 254, Dionex ICS-1100 devices), moisture, ash, volatile matter (using gravimetric methods) and to evaluate calorific values (IKA C-2000 Basic) of analysed fuels. The methodology was presented in Author’s previous works [4,6].

In calculations, maximum values of already introduced emission standards were adopted – in accordance to Directive 2010/75/EU (for SO₂, NO_x, dust) and BAT Reference Document for LCP (Hg, HCl) (see Table 3.). As a result, highest possible emission and fuel savings (using presented model and chosen energy carriers) were evaluated.

Table 3. Yearly average emission standards (all values at the STP: temperature 273.15 K and pressure 101.3 kPa, no water vapour content in gas and standardised O₂ content in gas equal to 6%) according to Directive 2010/75/EU on industrial emissions (IED) and BAT Reference Document for combustion plants using solid fuels with the total rated thermal input >300 MW [5,7]

Pollutant	Coal and lignite and other solid fuels		Biomass and peat	
	BAT	IED	BAT	IED
SO ₂ , mg/m ³	10-180	150-200	<10-100	150-200
NO _x , mg/m ³	50-175	150-200	40-160	150-200
Dust, mg/m ³	2-12	10-20	2-10	20
Hg, µg/m ³	< 1-7	-	<1-5	-
HCl, mg/m ³	< 1-7	-	1-25	-

To investigate the concentration of NO_x in raw fumes, empirical correlations for coal, lignite and biomass were included [8]. For hard coal and lignite, NO_x concentration in raw fumes was set as a level of 800 and 700 mg/m³_{st} (pulverized fuel boilers with tangential burner configurations), respectively, for biomass – 400 mg/m³_{st} (boiler with circulating fluidised bed).

3 Results

Calculated quality and quantity of raw fumes from the combustion of selected fuels were presented in Table 4. All values regarding emission standards were corrected to reference conditions. Additionally, CO₂ net emission factors were identified.

Table 4. Calculated quality and quantity of raw flue gas (for raw samples).

Fuel	L _{wet}	L _{dry}	O _{2dry}	S _{SO2}	S _{HCl}	S _{Hgtot}	S _{dust}	W _{CO2}	
	m ³ _n /kg	m ³ _n /kg	%	mg/m ³ _{st}	mg/m ³ _{st}	µg/m ³ _{st}	g/m ³ _{st}	kg/GJ	kg/MWh
hard coal	7.497	6.521	3.84	1109	161.1	9.16	27.2	97.32	875.8
lignite	5.348	4.270	3.75	4655	95.2	72.07	19.2	113.72	1023.5
solid biomass	5.923	4.859	3.67	238	458.7	5.65	11.6	107.08	963.76

Legend: L_{wet} – quantity of wet flue gases per 1 kg of fuel, L_{dry} – quantity of dry flue gases per 1 kg of fuel, O_{2dry} – concentration (by volume) of oxygen, S_{SO2} – sulphur dioxide concentration, S_{HCl} – hydrogen chloride concentration, S_{Hgtot} – total mercury concentration (>700°C), S_{dust} – fly ash concentration, W_{CO2} – CO₂ emission factors (kg of carbon dioxide per GJ energy accumulated in fuel and kg of carbon dioxide per MWh net introduced to the electrical grid)

Assuming that consumption of hard coal in Poland in 2015 (excluding electricity, gas, steam and air conditioning supply) reached 72.3 million tonnes (51% was consumed in power sector) and lignite – 63.1 million tonnes (99% was dedicated to power industry), the

adaptation of first NPP in Poland should lead to the decrease of consumption by 12% and 26% (in comparison with 2015), respectively [9]. Moreover, it would result in reducing the total annual emission of CO₂ in Poland by 5.7-6.8%, SO₂ by 2.0-2.3%, NO_x by 2.0-2.3%, dust by 0.01-0.05% and mercury by 2.6-5.3% (including new environmental emission standards). Calculated absolute quantities of emission savings for each of the fuel were presented in Table 5.

Table 5. Calculated emission and fuel savings after implementation of 3,000 MW NPP

Fuel	Fuel savings	CO ₂	SO ₂	NO _x	Dust	Hg
	milion tonnes		thous. tonnes		tonnes	kg
hard coal	8.9	17.6	13.57	13.57	1.36	271
lignite	16.4	21.29	16.10	16.10	1.61	564
biomass	13.1	20.04	14.71	14.71	1.47	294

4 Conclusions

The replacement of conventional, mostly coal-fired, professional power units in Poland by first nuclear power plant will result in significant emission and fuel savings. For instance, the 3,000 MW class NPP in 2015 would help to reduce the total annual emissions of CO₂ by 5.7-6.8% and mercury up to 5.3%. For SO₂, NO_x and dust emission, obtained emission savings would not exceed 3% each. Therefore, when introduced, first NPP in Poland will undoubtedly become a vital part of pro-environmental power sector and significantly decrease the emission rates of Polish economy (CO₂ emission factor for analysed hard coal stood at 876 kg/MWh_{net}, for biomass – at 964 kg/MWh_{net} and for lignite – at 1024 kg/MWh_{net}).

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