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Optimization of combined heat and power (CHP) market allocation: The case of Poland

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Optimization of combined heat and power (CHP) market allocation: The case of Poland

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Abstract. Combined heat and power (CHP), that is production of electricity and useful heat in a single thermodynamic process, is a way of primary energy saving and emission reduction. Therefore, promotion of the electricity from high-efficiency cogeneration (CHP-E) was encouraged in the European Union. However, CHP-E promotion mechanisms proved low effectiveness in certain countries, like Poland, where the prices of certificates of origin were kept at relatively low levels. This paper attempts to analyse the effect of CHP-E support system on the market allocation of different cogeneration technologies. MARKAL model of Polish power system was applied to calculate the installed capacity and annual electricity production from cogeneration plants in time perspective to 2030. The impact of buy-out fee and resulting shadow prices of certificates on the market share of CHP-E and the technology choice was studied. The convergence of promotion mechanisms for CHP-E and electricity from renewable energy sources (RES-E) was also investigated.

1. Introduction

1.1. *Overview.*

In Europe, a transformation period within the power sector is envisaged in both short- and long-term perspectives, as a result of climate policy and state policy under the EU legal framework [1]. In certain countries, e.g. Poland, the overwhelming share of power generating units are near to their shutdown date and new power units should be commissioned in short-term perspective [2]. Additionally, increase in the demand for electricity and heat has forced the development of technologies that enable the production of electricity and heat in more efficient technological process than that offered in separate heat and power generating systems. Production of heat and power in one thermodynamic process is commonly named combined heat and power (CHP) production and is compliant with the definition of cogeneration [3]. CHP allows to increase the overall efficiency of electricity and heat production, save the primary energy, and reduce the environmental impacts. Advantages of CHP encouraged European Commission (EC) to qualify it as a preferred technology to produce electricity and heat [4], as it was first shown in Directive 2004/8/EC [3]. The Directive was a legal framework for the promotion of high-efficiency cogeneration of useful heat and electricity or mechanical energy or both. As a consequence, new support mechanisms have been implemented in European Union (EU) Member States to make CHP technology more competitive on electricity and heat markets. CHP support mechanisms, based on quota obligations and tradable certificates of origin of electricity from different CHP technologies, were

legally implemented in EU. In Poland, selected as a case study in this paper, the Energy Act [5] and accompanying regulations constitute the law governing the promotion of electricity from high-efficiency cogeneration (CHP-E). However, the CHP-E promotion system, implemented in Poland in 2007, proved low effectiveness, as certificate prices were kept at the levels that did not effectively incentivise new CHP units construction [6,7]. Therefore, this paper attempts to analyse the future effect of CHP-E support system based on tradable certificates on the market allocation of different cogeneration technologies. The impact of buy-out fees and resulting shadow prices of certificates on the market share of CHP-E and the power generation technology choice was studied. The amount of installed capacity and CHP-E production in Poland in time period 2010-2030 were calculated. As CHP-E production depends on the level of CHP-E support, the shadow prices of certificates of origin of CHP-E were calculated and presented. There were examples of previously published results of cogeneration market analyses. Croatian cogeneration market was presented in [9–11] and included discussion concerning various concepts of district and individual heating systems. Incentives for CHP plants in the United States, included society versus owner costs and benefits, were studied in [12]. However, to our best knowledge, this paper is the first attempt of dealing specifically with the issue of the impact of CHP-E promotion mechanism, based on various types of tradable certificates, on the market allocation of different CHP technologies.

1.2. *CHP and energy saving.*

CHP plants can operate with the overall efficiency of 85-90%, while in separate electricity and heat production systems, these efficiencies can reach 55% and 81%, respectively. The former is achieved in combined cycle gas turbine power plants, while the latter in natural gas boilers. [8] As a result of the specific fuel consumption reduction during electricity and heat production, the primary energy savings (PES) are obtained. PES indicator, according to Cogeneration Directive [3], is based on the annual production of heat and electricity and consumption of primary fuel [9], and is calculated using the following formula:

$$PES = \left(1 - \frac{1}{\frac{\eta_{CHP-H}}{\eta_{Ref-H}} + \frac{\eta_{CHP-E}}{\eta_{Ref-E}}}\right) \cdot 100\% \tag{1}$$

where:

$\eta_{CHP-H/E}$	the efficiency of heat/electricity production in CHP system
$\eta_{Ref-H/E}$	the reference value of efficiency for heat/electricity production in separate systems

PES indicates the efficiency of cogeneration as follows: high-efficiency CHP is when PES $\geq$ 10% for units with installed capacity of more than 1 MW_e or has to be positive for smaller units.
CHP was the subject of previous system analyses.

1.3. *Overview of the CHP-E promotion mechanisms in Poland.*

The need for the reduction of the specific fuel consumption, primary energy savings and reduction of anthropogenic emissions of CO_2 to the atmosphere, caused the European Union to choose the CHP technology as one of the best solutions for protecting the environment and increasing the security of energy supply. In 2004, the European Parliament and European Council adopted a Cogeneration Directive 2004/08/EC [3], the aim of which was to promote CHP technologies. By the end of 2006, all EU Member States were obliged to implement support mechanisms and choose the authority to supervise the system. One of the support mechanisms was based on the certificates of origin of electricity. In Poland, the certificates of origin were issued by Energy Regulatory Office (ERO). CHP, in Polish energy system, are divided by the type of fuel and unit size. The certificates of origin have been informally named by assigning them to different colours depending on the type of produced electricity, namely: green - the electricity from renewable energy sources (RES-E), yellow - electricity from gas-fired CHP units or units with an installed capacity below 1 MW_e, violet - the electricity from methane-fired CHP units, and red - the electricity from CHP units not covered by other types, that is

usually coal-fired and bigger than 1 MW_e [5,13]. In 2014, Directive 2004/08/EC [3] was amended by Directive 2012/27/EU on energy efficiency [14], which put even greater emphasis on investments in CHP technologies. EU Members States are committed to support CHP investments, especially in distributed generation. The advantages of producing electricity and heat in CHP units have been also recognised in the *Energy Policy of Poland until 2030* [15]. The document determined the development of CHP as a main goal of establishing energy security of the country. Furthermore, the document assumed twofold increase of CHP-E until 2030, as compared to the year 2006.

1.4. *The barriers in CHP development in Poland.*

In Polish power system, there is a large economic potential of CHP, due to widely developed structures of district heating systems. This potential is not fullly utilised [16] because of economic, environmental, legislative, and social barriers. The economic barriers are high investments costs in CHP technologies combined with low profits from selling electricity and heat. The solution of this issue should be the support mechanisms in the form of tradable certificates of origin of CHP-E. The environmental barriers stem from the obligation of acquiring CO2 allowances, which significantly raises the operating costs. This obligation results from the provisions of The European Union Emission Trading Scheme (EU ETS) [17,18], also implemented in Polish legal framework [19]. The regulations concerning the promotion of CHP-E in Polish energy markets are unstable. Support mechanisms are defined for a short-term perspective, making it impossible to strictly predict future profits from CHP production [20]. An insufficient knowledge concerning small-sized CHP technologies represented by local governments and lack of competence in local energy planning are the main social barriers.

2. Methodology

### 2.1. *Overview of the MARKAL model of Polish power system.*

MARKAL modelling framework, documented in [21], was applied to study the effect of CHP-E promotion mechanism combined with a similar system for RES-E. In addition, EU ETS [17] was taken into account in the model. The planning horizon was divided into five-year periods between the years 2010 and 2030. The model year 2010 (planning period of 2010-2014) is the one, in which model calibration was made. In this period, the existing state of energy system was described by the set of mathematical equations and inequalities constraining the solution of the optimization model and reflecting current installed capacity and activity of the processes, that is the production of electricity or heat or both. Modelling period of 2015-2019 takes into account the investments in the power sector that are either completed or under construction within its time frames. Polish MARKAL model, applied in this research, was broadly analysed and described in [1]. Emission allowance prices were based on [22]. The model was improved by updating the projections of electricity and heat demand. In addition, the set of new industrial autoproduction CHP plants was added to the reference energy system, which is the structure of resources, commodities, technologies and demand categories [1,23].

2.2. *Modelling methodology of RES-E and CHP-E promotion mechanisms.*

The methodology was shortly described in [20,24]. In [20], the analysis of RES-E promotion mechanism with the use of Polish MARKAL was presented. In this paper, the authors focus on CHP-E support systems and the convergence or divergence of CHP-E and RES-E promotion schemes. The part of the reference energy system built for the purpose of modelling the system of tradable certificates of origin was presented in Figure 1.

The general idea of the method is as follows: CHP-E and RES-E generators, except for the electricity, can sell certificates of origin of a given type. The latter constitutes an additional revenue for them. Companies selling electricity to consumers are obliged to acquire and surrender to the regulatory body (in Poland - ERO), certificates of origin. The amount of electricity, that must be present on the surrendered certificates of origin, depends on the obligatory share for each type of certificate and the

amount of electricity sold to final consumers. The costs of acquiring certificates of origin are transferred to the demand side that is the consumers of electricity and heat.
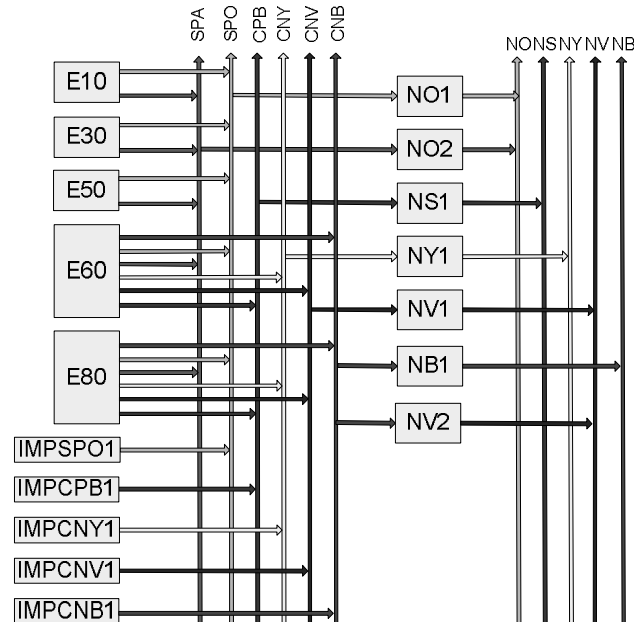
Figure 1. Reference Energy System for the renewable energy sources promotion mechanisms and high-efficiency cogeneration [20].

Note: NO - quota obligation - electricity from RES (green certificates), NS - quota obligation - electricity from high-efficiency cogeneration (red certificates), NY - quota obligation - high-efficiency cogeneration on natural gas or with capacity not exceeding 1 MW (yellow certificates), NV - quota obligation - high-efficiency cogeneration on methane from coal mines (violet certificates), NB - quota obligation - high-efficiency cogeneration on methane from biomass (brown certificates), SPO - certificates of origin from RES (PMOZE), CPB - certificates of origin from high-efficiency cogeneration (PMEC), SPA - certificates of origin from RES (PMOZE_A), CNY - certificates of origin - cogeneration on natural gas or with capacity not exceeding 1 MW (PMGM), CNV - certificates of origin - cogeneration on methane from coal mines (PMMET), CNB - certificates of origin - cogeneration on methane from biomass (PMBG), E10 - public thermal power plants – hard coal and lignite, E30 - independent power plants – renewable energy sources (RES), E50 –public hydro plants, E60 - public and independent cogeneration plants, E80 - industrial cogeneration plants, IMPSPO1 - buy-out fee – renewable energy sources, IMPCPB1 - buy-out fee - high-efficiency cogeneration (PMEC), IMPCNY1 - buy-out fee - high-efficiency cogeneration (PMGM), IMPCNV1 - buy-out fee - high-efficiency cogeneration (PMMET), IMPCNB1 - buy-out fee - high-efficiency cogeneration (PMBG)

The mathematical model of RES promotion mechanism was described below. The demand for certificates of origin is calculated on the basis of final electricity consumption:

$$DEMAND_{c,t} = share_{c,t} \cdot DEMAND(ELC)_t \qquad (2)$$

where:

$DEMAND_{c,t}$ demand for certificates of origin of type c in time period t [MWh/yr]

$DEMAND(ELC)_t$ final electricity demand in time period t [MWh/yr]

$share_{c,t}$ obligatory share of electricity of type c in final electricity demand in time period t [-]

The difference between the demand for certificates of origin and the total amount of certificates obtained and surrendered is a number of the certificates of origin shortfall, for which the buy-out fee is calculated as follows:

$$SHORTFALL_{c,t} \geq DEMAND_{c,t} - BALANCE_{c,t} \tag{3}$$

$$BYFEE_{c,t} = BYPRICE_{c,t} \cdot SHORTFALL_{c,t} \tag{4}$$

where:

$SHORTFALL_{c,t}$ the shortfall of certificates of origin of type c in time period t [MWh/yr]

$BALANCE_{c,t}$ the balance of (the amount of acquired and surrendered) certificates of origin of type c in time period t [MWh/yr]

$BYFEE_{c,t}$ penalty (buy-out fee) for the shortfall of electricity (certificate of origin) of type c in time period t [EUR'10/yr]

$BYPRICE_{c,t}$ penalty (buy-out fee) for the shortfall of one unit of electricity (certificate of origin) of type c in time period t [EUR'10/MWh]

2.3. Projections of final energy demand.

Final electricity demand projections (Figure 2) were updated in relation to [1]. The data on electricity consumption for a base year (2010) was taken from [25]. The projections were developed based on the methodology presented in [1]. It was assumed that electricity intensity of GDP will be reduced by 27% and electricity per capita consumption will grow by 20%, in both cases in a time period of 2010-2030. District heat demand projections were based on [26]. The data on process heat consumption were obtained from [27]. Projections of heat demand in Poland to 2030 were presented in Figure 3.
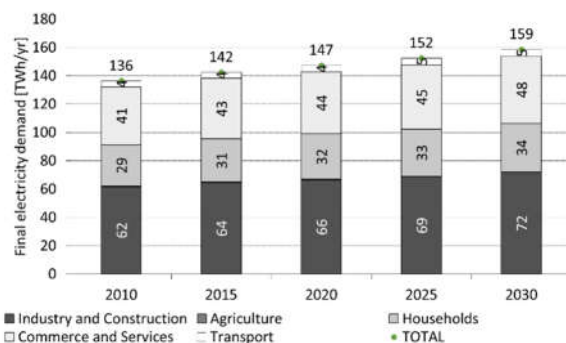
Figure 2. Projections of final electricity demand in Poland to 2030. Authors' illustration based on [1,25].
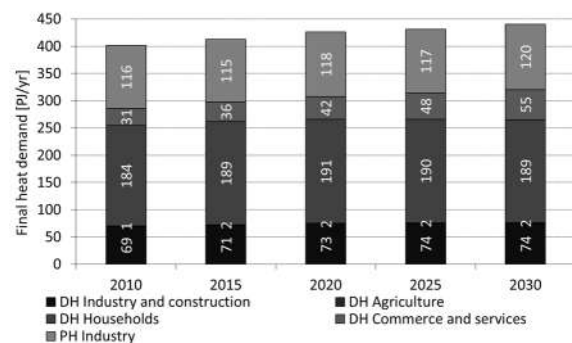
Figure 3. Projections of final district heat (DH) and process heat (PH) demand in Poland to 2030. Authors' illustration based on [26,27].

2.4. Cases description.

Four cases were envisaged for calculations, named C1 to C4. Cases C1 and C3 assume that the system of CHP-E promotion will be maintained until 2030, while cases C2 and C4 assume that after the year 2020, this system will no longer exist. To verify the convergence of CHP-E and RES-E systems, cases C1 and C2 assume the continuation of RES-E support, while cases C3 and C4 propose discontinuation of this scheme after 2020. Table 1 contains the summary of cases i.e. obligatory shares of each certificate of origin type in total final electricity consumption were presented. The mechanisms that were assumed to be continued after 2020 were given in brackets to facilitate the interpretation of cases. Buy-out fees, envisaged in the case of the shortfall of a certificate of origin, were presented in Table 2.

Table 1. Obligatory shares of each electricity type, defined by the type of certificates of origin, in total final electricity consumption – summary of the cases.
Authors' illustration based on [5].

Commodity	Case	2010	2015	2020	2025	2030
PMEC	C1 (CHP+RES), C3 (CHP)	21.3%	23.2%	23.2%	23.2%	23.2%
	C2 (RES), C4 (NONE)	21.3%	23.2%	0.0%	0.0%	0.0%
PMGM	C1 (CHP+RES), C3 (CHP)	3.9%	9.0%	12.0%	14.0%	15.0%
	C2 (RES), C4 (NONE)	3.9%	9.0%	0.0%	0.0%	0.0%
PMMET/ PMBG	C1 (CHP+RES), C3 (CHP)	1.1%	2.8%	3.1%	3.5%	4.0%
	C2 (RES), C4 (NONE)	1.1%	2.8%	0.0%	0.0%	0.0%
PMOZE/ PMOZE_A	C1 (CHP+RES), C2 (RES) C3 (CHP),	10.4%	18.0%	23.0%	28.0%	33.0%
	C4 (NONE)	10.4%	18.0%	0.0%	0.0%	0.0%

Table 2. Buy-out fees for certificates of origin [EUR'10/MWh].
Authors' illustration based on ERO reports and predictions.

Commodity	Case	2010	2015	2020	2025	2030
O_{zj} (PMOZE / PMOZE_A)	ALL*	60	59	66	63	62
O_{zk} (PMEC)	ALL*	7	2	2	2	1
O_{zg} (PMGM)	ALL*	35	23	24	25	26
O_{zm} (PMMET / PMBG)	ALL*	14	11	13	14	16

* Please note that in cases assuming withdrawal from promotion mechanisms, the prices will be set to zero after 2020

3. Results

Planned electricity production in Poland, in time perspective from 2010 to 2030, was presented in **Table 3**. Planned installed capacity in CHP plants in Poland, in the same time frames, was depicted in **Table 4**. These results of model runs show that the production levels in CHP plants are slightly affected by the CHP-E promotion mechanism in time perspective to 2030. Discontinuation of CHP-E promotion after the year 2020 (Cases C2 and C4) results in similar production levels and CHP-E shares as in cases C3 and C1, in which this system is continued. This may be a result of several factors. Firstly, RES-E promotion system and EU ETS are in place and they both can have a greater impact on the choice of power generation technologies than CHP-E promotion mechanism. Secondly, the decisions on building new CHP plants in Poland have been taken and there are projects under way, which were assumed to be built in the model analysis in time periods 2015 and 2020. However, in all cases, the increase in the total electrical installed capacity in CHP plants and in the share of CHP-E in total electricity production is observed. This results from the stable, but slow growth of electricity and heat demands and the increase in the prices of fuels, environmental fees and emission allowances. These factors are the main incentives for turning the attention of investors to energy-saving options, including cogeneration, within considered time perspective. Since the share of electricity from CHP plants in 2006 was 18.9% [28], the goal of doubling this share to 2030, adopted in [15], is not achieved under modelled market conditions.

Table 3. Planned electricity production in Poland in 2010-2030 period [TWh/yr].

Planning period	2010	2015	2020		2025		2030		
Case	ALL	ALL	C1, C2	C3, C4	C1, C2	C3, C4	C1	C2	C3, C4
Coal PP	112.6	97.0	84.4	103.6	68.0	99.9	62.3	62.4	88.4
Hydro and RES - existing	4.8	4.7	4.5	4.2	4.6	4.4	4.9	4.9	4.9
RES - new	0.8	9.6	25.6	7.9	37.1	7.9	47.0	47.0	20.8
CHP DH - exisiting	24.7	23.5	20.7	20.7	18.8	18.0	14.5	14.5	14.5
CHP DH Coal - new	0.0	0.2	1.8	1.8	11.5	11.5	15.3	15.3	15.3
CHP DH Gas - new	0.0	0.9	0.0	0.0	0.0	0.0	1.2	1.1	2.2
CHP DH Biomass - new	0.0	0.1	0.2	0.2	0.2	0.2	0.2	0.2	0.2
CHP DH Biogas - new	0.0	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.0
CHP PH - existing	6.6	5.8	3.9	3.8	2.6	2.5	1.6	1.6	1.6
CHP PH Coal - new	0.0	1.4	5.4	5.6	7.8	8.0	10.2	10.2	10.2
Net import	-1.4	10.2	10.2	10.2	10.2	10.2	10.2	10.2	10.2
TOTAL	148.0	153.4	156.9	158.2	160.9	162.6	167.5	167.5	168.5
TOTAL CHP-E DH	24.7	24.7	22.9	22.9	30.6	29.8	31.3	31.2	32.3
TOTAL CHP-E PH	6.6	7.2	9.3	9.4	10.4	10.5	11.8	11.8	11.8
TOTAL CHP-E	31.3	31.9	32.2	32.3	41.0	40.3	43.1	43.0	44.1
CHP-E share	20.9%	22.3%	22.0%	21.8%	27.2%	26.5%	27.4%	27.4%	27.9%

Table 4. Current and planned electrical installed capacity of CHP plants in Poland in 2010-2030 period [MW_e].

Planning period	2010	2015	2020		2025		2030		
Case	ALL	ALL	C1, C2	C3, C4	C1, C2	C3, C4	C1	C2	C3, C4
CHP DH - exisiting	5979	5642	4977	4977	4282	4282	3315	3315	3315
CHP DH Coal - new	0	51	479	479	2979	2979	3979	3979	3979
CHP DH Gas - new	0	149	764	764	764	764	764	764	764
CHP DH Biomass - new	0	13	50	50	50	50	50	50	50
CHP DH Biogas - new	0	14	14	14	14	14	14	14	14
CHP PH - existing	1792	1604	1226	1226	944	944	661	661	661
CHP PH Coal - new	0	375	1400	1453	2011	2068	2644	2657	2665
TOTAL CHP DH	5979	5868	6283	6283	8088	8088	8121	8121	8121
TOTAL CHP PH	1792	1979	2626	2679	2955	3012	3305	3318	3326
TOTAL CHP	7771	7846	8908	8962	11042	11099	11425	11438	11447

Shadow prices of certificates of origin, presented in **Table 5**, were calculated by MARKAL model as a dual solution of balance equations of corresponding commodity. They are the values of objective function change as a result of the change of one unit of energy/commodity in balance equation. Their economic interpretation is similar to marginal cost – the cost of introducing additional unit of commodity to the energy system. Zero values indicate that the CHP-E or RES-E promotion mechanism is not in

place in this period. In cases, where promotion mechanisms are continued, these shadow prices take the values that are either equal or very close to the assumed buy-out fees for corresponding certificates, which indicate that there is no oversupply of them.

Table 5. Shadow prices of certificates of origin [EUR'10/MWh].

Commodity	Case	2010	2015	2020	2025	2030
PMMET (CNV) / PMBG (CNB)	C1 (CHP+RES), C3 (CHP)	14.1	10.9	12.5	14.4	16.5
	C2 (RES), C4 (NONE)	14.1	10.9	0.0	0.0	0.0
PMGM (CNY)	C1 (CHP+RES), C3 (CHP)	35.1	23.4	24.3	25.4	26.3
	C2 (RES), C4 (NONE)	35.1	23.4	0.0	0.0	0.0
PMEC (CPB)	C1 (CHP+RES), C3 (CHP)	7.0	1.9	1.9	1.7	1.4
	C2 (RES), C4 (NONE)	7.0	1.9	0.0	0.0	0.0
PMOZE (SPO) / PMOZE_A (SPA)	C1 (CHP+RES), C2 (RES) C3 (CHP), C4 (NONE)	60.1	58.5	66.1	61.6	60.3
	C4 (NONE)	60.1	58.5	0.0	0.0	0.0

4. Conclusions

The analysis shows that in medium-term perspective (to 2030) and with further decrease in buy-out fees and stabilised obligatory share of CHP-E, these mechanisms prove to have low effect on the technology choice. Other systems, for example RES-E promotion and EU ETS, can be the driving force for technology alterations in energy systems towards increased use of cogeneration. In order to stimulate the growth of CHP-E production, the increase in buy-out fees and stable growth of obligatory shares for CHP-E should be adopted in legal framework. However, the design of legal regulation should take into account technical and economic potentials of both large-scale and small-scale cogeneration. Coal-based CHP technologies are predicted to be the first choice due to low hard coal prices. However, a potential increase in emission allowance prices within EU ETS, driven by the introduction of Market Stability Reserve to the system and further decrease in EU ETS cap, may constitute a major threat for their operation in long-term perspective, not covered by the model, that is 2030-2050. Decarbonization strategy, proposed in EU, will encourage the technological transition towards biomass- or biogas-based CHP units, which have a limited potential resulting from high costs of biomass transport to the plant and social opposition to biogas plants. Natural-gas-based cogeneration can be represented by a variety of technologies covering wide range of sizes, that is microturbines for microcogeneration, gas engines for small-scale cogeneration, gas turbines and combined cycle gas turbines for large-scale cogeneration. From this point of view this may be a promising choice. However, increasing prices of natural gas limit their applications due to the threat of economic unviability of such projects.

References

[1]   Jaskólski M 2016 Modelling long-term technological transition of Polish power system using
       MARKAL: Emission trade impact *Energy Policy* **97** p. 365–377

[2]   Polish Information and Foreign Investment Agency, Energy Sector in Poland, Warsaw, 2013.

[3]   European Commission 2004 DIRECTIVE 2004/8/EC OF THE EUROPEAN PARLIAMENT
       AND OF THE COUNCIL of 11 February 2004 on the promotion of cogeneration based on a
       useful heat demand in the internal energy market and amending Directive 92/42/EEC, Off. J.
       Eur. Union. p. 50–60

[4]   Jaskólski M, Reński A and Minkiewicz T 2017 Thermodynamic and economic analysis of
       nuclear power unit operating in partial cogeneration mode to produce electricity and district
       heat, *Energy* **141** p. 2470 - 2483

[5]   2014 Ustawa z dnia 10 kwietnia 1997 r. Prawo energetyczne, Dz.U. 1997 Nr 54 Poz. 348. 2006

[6]   Sołtysik M, Mucha-Kuś K 2015 High-efficiency Gas Cogeneration – an Assessment of the
       Support Mechanism, *Acta Energ*. **3** () 97–102. doi:10.12736/issn.2300-3022.2015309.

[7]   Sołtysik M and Mucha-Kuś K 2014 Influence of Regulations on Market Efficiency from the
       Viewpoint of High-efficiency Cogeneration, *Acta Energ*. **20** p. 134–139

[8]   Moreira N A, Monteiro E and Ferreira S 2007 Transposition of the EU cogeneration directive:
       A vision for Portugal, *Energy Policy* **35** p. 5747–5753

[9]   Lončar D, Duić N and Bogdan Ž 2009 An analysis of the legal and market framework for the
       cogeneration sector in Croatia, *Energy* **34** p. 134–143

[10] Lončar D and Ridjan I 2012 Medium term development prospects of cogeneration district
       heating systems in transition country - Croatian case, *Energy* **48** p. 32–39.
       doi:10.1016/j.energy.2012.07.025.

[11] Lipošćak M, Afgan N H, Duić N and da Graça Carvalho M 2006 Sustainability assessment of
       cogeneration sector development in Croatia, *Energy* **31** p. 1940–1948

[12] Athawale R and Felder F A 2014 Incentives for Combined Heat and Power plants: How to
       increase societal benefits?, *Util. Policy* **31** p. 121–132

[13] Paska J, Sałek M and Surma T 2009 Current status and perspectives of renewable energy
       sources in Poland, *Renew. Sustain. Energy Rev* **13** p. 142–154

[14] 2014 Directive 2012/27/EU of the European Parliament and of the Council of 25 October 2012
       on energy efficiency, amending Directives 2009/125/EC and 2010/30/EU and repealing
       Directives 2004/8/EC and 2006/32/EC

[15] 2009 Ministry of Economy of the Republic of Poland, Energy Policy of Poland until 2030 -
       Appendix to Resolution no. 202/2009 of the Council of Ministers of 10 November 2009

[16] Lewandowski J 2010 *Opracowanie założeń i kluczowych elementów „Programu Rozwoju w
       Polsce Kogeneracji"*

[17] 2013 European Commission, The EU Emissions Trading System (EU ETS), Clim. Action.

[18] 2009 European Commission, Directive 2009/29/EC of the European Parliament and of the
       Council of 23 April 2009 amending Directive 2003/87/EC so as to improve and extend the
       greenhouse gas emission allowance trading scheme of the Community, Official Journal of
       the European Union L 140/63

[19] Ministry of the Environment of the Republic of Poland 2011 The act dated 28 April 2011 on the
       greenhouse gas emission allowance trading (in Polish), *Dz.U. 2011 nr 122 poz. 695,*.

[20] Jaskólski M and Bućko P 2015 MARKAL long-term power generation scenarios for Poland:
       Increasing the share of renewable energy sources by 2040, *Rynek Energii* **117** p. 117–125

[21] Loulou R, Goldstein Gand Noble K 2004 Documentation for the MARKAL Family of Models

[22] Ministry of Economy of the Republic of Poland 2015 Energy policy of Poland until 2050 - The
       draft version 0.6 dated 03 Aug 2015 (in Polish)

[23] Jaskólski M 2012 Application of MARKAL model to optimisation of electricity generation
       structure in Poland in the long-term time horizon Part I – concept of the model, *Acta Energ*
       12 p. 15–25

[24]   Jaskólski M 2012 Application of MARKAL model to optimisation of electricity generation
        structure in Poland in the long term time horizon . Part II . Model and forecasts assumptions,
        Acta Energ **13** p. 4–13

[25]   Agencja Rynku Energii S.A. 2015 Statystyka Elektroenergetyki Polskiej 2014 (Polish Power
        Sector Statictics 2014), *Agencja Rynku Energii S.A.*

[26]   PwC, Rynek ciepła w Polsce, 2012.

[27]   GUS 2016 Energy Statistics in 2014 and 2015, Central Statistical Office

[28]   Sołtysik M 2013 Wybrane aspekty funkcjonowania systemów wsparcia na przykładzie
        wysokosprawnej kogeneracji, *Tauron Pol. Energ. SA.*