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The operational water consumption of energy production: Czech Republic case study

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Abstract

Thermoelectric power plants require large amounts of cooling water. The energy sector is responsible for the largest annual volume of water withdrawals in the Czech Republic. It is a similar situation as in other countries in the world. Many reports have identified the water consumption of various energy production technologies around the world. This study is aimed at determining water withdrawals and water consumption per 1 MWh of energy produced in thermoelectric power plants in the Czech Republic. For the study 33 operational units were selected and considered individually. Real data on electricity and heat production and on water use were available for these operational units. The study included plants with a wide range of installed capacity of the order from tens of MW (MWe + MWt) up to units of GW. Most assessed plants use water recirculation cooling (closed cycle cooling). The individually assessed plants had flow (once-through) system, a combination of flow system with circulation system, and plants with a combination of flow with dry cooling system.

Keywords

energy production, water consumption, water-energy nexus, water withdrawals,

1. INTRODUCTION

Water is needed for energy and energy is needed for water. Energy production is generally water-intensive. Meeting ever-growing demands for energy will generate increasing stress on freshwater resources with repercussions for other users, such as agriculture and industry. Since these sectors also require energy, there is room to create synergies as they develop together [WWAP 2015]. The largest water users in the energy sector are thermoelectric power plants and hydropower plants which generally require large quantities of water. Thermoelectric power generation is a broad category of power plants consisting of coal, nuclear, oil, natural gas, and the steam portion of gas-fired combined cycles [Feeley III et al. 2008]. Approximately 90 % of global power generation is water intensive. Water is used directly for hydropower generation as well as for all forms of thermal power generation schemes [WWAP 2014]. Water is required not only in thermoelectric power plants but also to produce nearly all forms of energy.

For primary fuels, water is used in resource extraction, irrigation of biofuels feedstock crops, fuel refining and processing, and transport. In power generation, water provides cooling and other process-related needs at thermoelectric power plants; hydropower facilities harness its movement for electricity production [IEA 2012].

Globally, a little more than 4 000 km^3 of fresh water is withdrawn each year for human use. Of that, about 70 % is withdrawn for agriculture and around 10% for the power industry [Williams and Simmons 2013]. There is a completely different situation in the Czech Republic. As shown in the annual report on water management in the Czech Republic in the period 2004-2013, the energy sector withdrew an average of 44.98% of all withdrawals from water resources in the Czech Republic and 56.07% if observing only surface waters.

The issues related to water demand and its determinants were considered in several earlier studies of thermoelectric water use. Examples of these studies can be found for example in [Dziegelewski and Bik [2006]. The group of operational conditions can include, in particular, technology of boilers, type of cooling systems and the way of dealing with fly ash and its transport. Because in conventional power plants half or more of the produced heat gets lost as waste heat [WWAP 2014], most power plants operate in a combined heat and power mode in the Czech Republic. And, conversely, most heating plants use power generation to maintain optimal operating conditions of boilers in periods of reduced heat demand. For this paper we use the term "power plant" for a classic power plant and also for a heating plant with power generation.

The design of a cooling system and its operational condition is the most important factor for water withdrawals and water consumption in thermoelectric power generation. Generally, higher withdrawals and lower consumptions of water per produced energy unit are typical for power plants with once-through (open loop) cooling systems. Conversely, lower withdrawals with higher consumption per energy unit are typical for recirculating (close loop) cooling systems [Macknick et al. 2012].

In the group of natural condition we can include water availability, temperature, air humidity, etc.

Social and economic conditions are very important in a longer perspective because they are the basis for investment decisions about improvement of technology of current plants, design of new plants, etc. The influence of indirect factors cannot be expressed exactly, but we can use econometrics tools to answer "how much" questions using theory and data from economics, business, statistics, as well as social and natural sciences [Hill et al. 2012]. Econometrics come into play either when we have an economic theory to test or when we have a relationship in mind that has some importance for policy decisions or analyses [Wooldridge 2009].

2. MATERIAL AND METHODS

2.1 Water usage and energy production

In our study we focused on the operational phase of power generation, thus excluding water usage in other stages of the life cycle [Fthenakis and Kim 2010; Williams and Simmons 2013].

For the study presented within this paper we collected data from evidence of water balance under Decree no. 431/2001 Coll. In most cases we examined permitted withdrawals and discharges in the IPPC licence. For the next solution we selected plants for which there were data on withdrawals and discharges. Some power plants must be grouped into the operational units because only data about withdrawals and discharges for operational units are available. For these power plants we obtained data on the production of electricity (MWe) and heat energy (MWt) and additional data from individual operators of these power plants. For the study 33 operational units were selected (see Table 1) and considered individually. The study included power plants with a wide range of installed capacity of the order from tens of MW (MWe + MWt) up to units of GW. The data availability determined the time period of the study to the decade 2004-2013.

For operational units for which data are only available on net electricity production, gross electricity generation was calculated by using average ratio gross and net electricity generation from records with both data.

Records which are not used for direct production of energy were excluded from the withdrawals and discharges data. Typically they are remediation pumping, cases of watercourse flowing through ash landfills, water supply to other users, etc.

2.2 Factors determining water needs for energy production

We assumed that water demand per energy unit is a function of direct and indirect determinants. As determinants describing natural conditions we selected average annual temperature and average temperature from June to September representing of the period with most intensive demand on cooling. As the determinants describing operational conditions we selected the amount of produced energy, heat energy to total energy production ratio, capacity factor - electricity, capacity factor - heat, and type of cooling equipment. The amount of produced energy includes both electrical and heat energy. The capacity factor - electricity (resp. heat) of an operation is the ratio of its actual electricity (resp. heat) output over a period of time, to its potential electrical (resp. heat) output if it were possible for it to operate at full electric (resp. heat) generation capacity (also known as nameplate capacity) continuously over the same period of time. As determinants describing socio-economic condition we selected payments for water withdrawals. For these determinants we collected data from the Czech Statistical Office and other sources. The type of cooling equipment was the only (purely) qualitative determinant and we divided the operations into groups accordingly.

The remaining seven determinants are quantitative and served as explanatory variables in the regression analysis described below.

As the main target of the study is the connection between thermoelectric sector as a whole and water withdrawal, we also took into account the relative energy production of individual operations. That means that each operation received the weight equal to its share on the sum of energy produced by all operations included in the relevant model. This approach contributes to reduce the (total) error of prediction when trying to predict the total amount of water withdrawn in a certain future year. In practice, a possible expected error of, for example, 0.1 m^3/MWh gets more weight concerning large operations than 0.1 m^3/MWh concerning small operations. However, we also tried to estimate the influence of the determinants without weighting the individual cases. This approach can be useful for predicting the withdrawals of smaller operations, either individually or when grouped. The determinant amount of produced energy, mentioned in the previous paragraph as an explanatory variable, may be useful for more accurate prediction of individual withdrawals and serves rather as a feature of an individual operation. Using the size of an operation as an explanatory variable does not interfere with weighting the cases by practically the same variable.

The operations listed in Table 1 were divided into three groups. The first group represents operations with once-through cooling system. The second group represents operations with recirculating cooling system, and the third represents hybrid cooling systems. This study focuses only on the first two groups because there were only two operation units with a hybrid system. So we got a group of 28 records in annual steps for operations with once-through cooling systems and 5 records for recirculating cooling system. These two groups of records were analysed with SPSS statistical software. For each group we tried to find the best model using weighted least squares regression and the best model using least squares regression without weighting. Therefore we searched for four models, each of them suitable for a different purpose or type of cooling.

Besides (not-) weighting the cases the process of searching for the best model was the same for all four segments. The dependent variable was water withdrawal per energy produced and the examined explanatory variables were always the seven quantitative variables mentioned in the first paragraph of section 2.2. We used the classical linear regression model in the form:

$$Y = \beta_0 + \beta_1 X_1 + \beta_2 X_2 + \ldots + \beta_n X_n + \varepsilon \qquad (1)$$

Where Y is the dependent variable (water withdrawals), β_i are regression coefficients, X_i are independent variables and ε is a random component (white noise). The models (i.e. sets of one to n explanatory variables, their regression parameters and other statistics) were generated with the procedures known as forward selection, backward selection and stepwise selection. For each model we estimated the Akaike information criterion (AIC) of the model and in the next step only examined models with the lowest AIC in the particular segment and with appropriate signs of the regression parameters. We require positive dependence for both temperatures and negative dependence for energy production, heat energy to total energy and for price of withdrawals. We are not sure about the required signs of the regression parameters of the variables capacity factor - electricity and capacity factor - heat. Both signs were therefore acceptable for us. The proposed models had the lowest AIC of the models which we examined in each segment and which fulfilled the signs requirement.

Tab 1. Summary of operations -average data for period 2004-2013

Operation	Gross energy generation per year [MWh]	Ratio between power and heat generation	Water withdrawals per energy unit [m^3/MWh]	Water consumption per energy unit [m^3/MWh]
HPs Brno Sever+Špitálka*	825510	0.168	1.337	0.798
HP České Budějovice	1024075	0.193	1.321	1.175
HP Dvůr Králové	154163	0.132	21.584	2.399
HPs Energetika Třinec	2166807	0.449	4.983	2.622
HP Kolín	415099	0.135	18.443	0.616
HP Liberec	280130	0.101	1.181	0.992
HP Olomouc	832410	0.319	0.539	0.388
HP Ostrov	123615	0.105	3.105	2.086
HP Otrokovice	780256	0.36	1.207	0.914
HP Písek	155836	0.099	0.437	0.372
HP Planá nad Lužnicí	337921	0.871	2.873	2.486
HP Plzeň	1576252	0.634	1.658	1.402
HP Přerov	672558	0.687	3.643	3.031
HP Strakonice	365548	0.483	13.915	0.625
HP Trmice	1439117	0.407	3.626	1.411
HP Varnsdorf	74440	0.079	5.37	2.156
HP Zlín	683066	0.411	1.004	0.918
PPs Alpiq Kladno	2188569	2.675	2.163	1.011
PP Dětmarovice	2646007	14.048	2.043	1.346
PP Hodonín	607782	1.793	114.772	0.424
PP Chvaletice	3125041	60.779	3.082	2.104
PP Ledvice	2338291	6.091	3.281	1.352
PP Mělník	7637173	1.887	53.242	1.602
PP Opatovice	3514978	1.529	50.719	0.503
PP Počerady	6699537	143.422	2.475	1.934
PP Poříčí	1098995	1.323	2.066	0.93

Operation	Gross energy generation per year [MWh]	Ratio between power and heat generation	Water withdrawals per energy unit [m^3/MWh]	Water consumption per energy unit [m^3/MWh]
PPs Prunéřov	8803992	20.03	2.341	1.841
PP Tisová	1869319	4.533	2.342	0.841
PP Tušimice	4021132	19.425	2.032	1.674
PP&HP Komořany	1520382	1.122	1.778	1.106
PP&HP Vřesová	7057527	1.043	1.805	0.581
NP Dukovany	14426350	108.981	3.376	2.079
NP Temelín	13295602	86.429	2.553	1.979

**Abbreviation: HP -heat power, NP - nuclear power plant, PP -fossil power plants*

The first group included 10 cases (each case for the particular year of the period 2004-2013) for each of the 28 operations with recirculating cooling. Therefore the regression parameters related to the already mentioned determinants were estimated from 280 cases during the regression analysis. The second group included 10 cases for each of the 5 operations, making the size of the sample 50 cases.

3. RESULTS

The results of analyses operational water withdrawals and consumption for energy generation shown in Table 1 are similar to the published results of other studies [Macknick et al. 2012].

3.1 Operations with recirculation cooling

The Table 2 shows the estimated regression parameters, standard error of the estimation, standardized coefficients, t value of the relevant variable and its statistical significance and collinearity statistics VIF. The bottom part of the table shows the statistics of the models as a whole. In all tables the models are ordered according to the values of their AIC.

The first three best models (using the AIC) in the recirculating cooling category contained the variable price for withdrawal and its parameter's sign was positive according to the regression analysis. The model with the lowest AIC in the category exhibits AIC equal to 1776,8 which is close to the AIC of the models 3re,w,f and 5re,w,b that are the models with fourth and fifth lowest AIC. These models contained three explanatory variables each and none of their regression parameters interferes with its expected sign. The values of R^2_{adj} indicate that the models 3re,w,f and 5re,w,b could have slight to moderate predictive power.

The Table 3 shows the best three models and their parameters if the operations receive equal weight. We can see that the models include the capacity factor of electricity production and also of heat production again. The signs of the regression parameters are the same as in the weighted regression case. On the other hand the R^2_{adj} of the models are low. As a result, the values of R^2_{adj} and F Significance are empirical evidence why (for the whole sector prediction) the models mentioned in the Tab 3 (i.e. models which take into account the size of individual operations) should be preferred. This may be confirmed by the lower values of AIC in weighted regression models however it is a question whether AIC is the best criterion for comparison of model estimated from equally weighted cases with model estimated from differently weighted cases.

3.2 Operations with once-through cooling

All of the three models for once-through cooling systems by energy production of individual operational units with the lowest AIC had the signs of their regression coefficients in accordance with our expectation (without considering the capacity factors). Apparently the values of the regression parameters of the same variables are in the models 3ot,w,b and 6ot,w,f very similar, which suggests that the explanatory variables, at least in the 3ot,w,b, could be very significant in once-through cooling segment. The Table 4 indicates that both models exhibit very high R^2_{adj}. According to the values of AIC we recommend the model 3ot,w,b.

The Table 5 shows the first and the third best models and their parameters in case the operations receive equal weight. The regression parameter of the variable avg. annual temperature of the second best model exhibited minus sign, however in the next step this variable was eliminated because of its low significance (0,922). The elimination of average annual temperature resulted in the model 2ot,b. The model 2ot,b is the model with the lowest AIC in this segment and the signs of its regression parameters are in accordance with the expectations.

4. DISCUSSION AND CONCLUSIONS

For circulation plants it is not possible to recognize from the available water balance data what was actually used for energy production. If there are no data on technological or hot water delivery to other water consumers, then the processed data can be significantly overstated. For example at the heating plant Planá nad Lužnicí unadjusted sampling of water supplies to third parties causes the increase in demand for water per 1 MWh by 68.7 % and water consumption by 79.4 % !!! Collecting information about the hot water supplies to third parties is unfortunately very complicated.

The results of the regression analysis suggests that the created models seem to be rather partially successful for the recirculation cooling category of operation and much more successful for the once-through cooling category. For most models with optimal or close to optimum values of AIC the expected signs of the estimated coefficients of explanatory variables were in accordance with the apriori expected signs.

Possible reasons of the relatively low prediction power of the models for recirculation cooling category include:

- more heterogeneous category (while once-through cooling uses the water just once, the number how many times the water is used in the recirculation system is not the same for all operations with recirculation system);

- not enough complex statistical model;
- the data availability only in annual step (while the electricity and heat production and temperature exhibits more variance during changing seasons or months rather than years).

Tab 2. Summary of analysis for best two models in category recirculating cooling – weighted by energy production of individual operational units

Model	Explanatory var.	Unstandardized Coeff.		Stand. Coeff.	t	Sig.	VIF
		β_i	Std. Error				
3re,w,f	(Constant)	-0,657	1,00		-0,66	0,511	
	capacity factor–electr.	1,553	0,28	0,369	5,49	0,000	1,6
	avg. temp.:June-Sept.	0,141	0,06	0,135	2,46	0,015	1,0
	capacity factor–heat	-0,786	0,47	-0,111	-1,67	0,097	1,5
5re,w,b	(Constant)	1,713	0,22		7,71	0,000	
	capacity factor–electr.	1,990	0,37	0,473	5,42	0,000	2,6
	capacity factor–heat	-1,662	0,55	-0,235	-3,03	0,003	2,1
	total energy prod.	-3,7E-08	0,00	-0,245	-2,39	0,018	3,6
Model	**no. of explanat. variables**	R^2_{adj}	**Std. Error of the Estimate**	**RSS**	F	F **Sig.**	**AIC**
3re,w,f	3	0,195	0,042	0,483	23,5	0,000	-1775,4
5re,w,b	3	0,194	0,042	0,484	23,4	0,000	-1775,1

Tab 3. Summary of analysis for best two models in category recirculating cooling – equal weight assigned to each of the operations

Model	Explanatory var.	Unstandardized Coeff. β_i	Unstandardized Coeff. Std. Error	Stand. Coeff.	t	Sig.	VIF
1re,f	(Constant)	1,935	0,18		10,77	0,000	
	capacity factor–electr.	0,927	0,33	0,164	2,78	0,006	1,0
2re,f	(Constant)	2,169	0,28		7,79	0,000	
	capacity factor–electr.	0,760	0,37	0,135	2,07	0,039	1,2
	capacity factor–heat	-0,881	0,80	-0,072	-1,10	0,271	1,2
3re,f	(Constant)	2,512	0,43		5,91	0,000	
	capacity factor–electr.	0,695	0,37	0,123	1,87	0,063	1,2
	capacity factor–heat	-1,113	0,83	-0,090	-1,34	0,180	1,3
	price for withdr.	-0,082	0,08	-0,065	-1,07	0,287	1,1
Model	**no. of explanat. variables**	R^2_{adj}	**Std. Error of the Estimate**	**RSS**	F	F **Sig.**	**AIC**
1re,f	1	0,023	1,181	387,7	7,7	0,006	93,1
2re,f	2	0,024	1,181	386,0	4,5	0,012	93,9
3re,f	3	0,025	1,180	384,4	3,4	0,019	94,8

Tab 4. Summary of analysis for best two models in category once-through cooling – weighted by energy production of individual operational units

Model	Explanatory var.	Unstandardized Coeff.		Stand. Coeff.	t	Sig.	VIF
		β_i	Std. Error				
3ot,w,b	(Constant)	160,74	42,32		3,80	0,000	
	price for withdr.	-41,02	7,65	-0,253	-5,36	0,000	1,9
	avg. temp.:June-Sept.	5,741	1,88	0,142	3,05	0,004	1,9
	heat e. to total energy	-216,48	11,07	-1,323	-19,6	0,000	4,0
	capacity factor–electr.	-87,11	21,45	-0,429	-4,06	0,000	9,7
	total energy prod.	-0,000012	0,00	-0,614	-6,05	0,000	9,0
6ot,w,f	(Constant)	163,38	43,83		3,73	0,001	
	capacity factor–heat	24,90	90,84	0,028	0,27	0,785	9,2
	price for withdr.	-39,73	9,04	-0,245	-4,40	0,000	2,7
	heat e. to total energy	-221,95	22,88	-1,356	-9,70	0,000	16,7
	total energy prod.	-0,000012	0,00	-0,630	-5,34	0,000	11,9
	capacity factor–electr.	-90,69	25,30	-0,446	-3,59	0,001	13,3
	avg. temp.:June-Sept.	5,618	1,96	0,139	2,87	0,006	2,0
Model	**no. of explanat. variables**	R^2_{adj}	**Std. Error of the Estimate**	**RSS**	F	F **Sig.**	**AIC**
3ot,w,b	5	0,944	0,931	38,2	166,0	0,000	-3,5
6ot,w,f	6	0,943	0,941	38,1	135,4	0,000	-1,6

Tab 5. Summary of analysis for best two models in category once-through cooling – equal weight assigned to each of the operations

Model	Explanatory var.	Unstandardized Coeff.		Stand. Coeff.	*t*	Sig.	VIF
		β_i	Std. Error				
2ot,b	(Constant)	124,24	47,23		2,63	0,012	
	price for withdr.	-51,46	7,54	-0,306	-6,82	0,000	2,7
	avg. temp.:June-Sept.	7,492	2,14	0,157	3,50	0,001	2,7
	heat e. to total energy	-185,40	18,85	-1,092	-9,83	0,000	16,6
	capacity factor–electr.	-54,23	23,84	-0,225	-2,27	0,028	13,2
	capacity factor–heat	-130,83	59,60	-0,146	-2,20	0,034	5,9
	total energy prod.	-0,000011	0,00	-0,369	-5,99	0,000	5,1
3ot,b	(Constant)	172,64	43,55		3,96	0,000	
	price for withdr.	-44,59	7,15	-0,265	-6,23	0,000	2,2
	avg. temp.:June-Sept.	5,530	2,03	0,116	2,73	0,009	2,2
	heat e. to total energy	-220,76	10,21	-1,300	-21,6	0,000	4,5
	capacity factor–electr.	-94,61	15,82	-0,392	-5,98	0,000	5,3
	total energy prod.	-0,000012	0,00	-0,390	-6,15	0,000	5,0

Model	no. of explanat. variables	R^2_{adj}	Std. Error of the Estimate	RSS	*F*	*F* Sig.	AIC
2ot,b	6	0,964	7,448	2385,5	217,2	0,000	205,3
3ot,b	5	0,960	7,765	2652,8	238,9	0,000	208,6

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